# A Scalable Architecture for Ordered Parallelism

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Massachusetts Institute of Technology

CSAIL

NVIDIA

# Multicores Target Easy Parallelism

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**Regular:** known tasks and data

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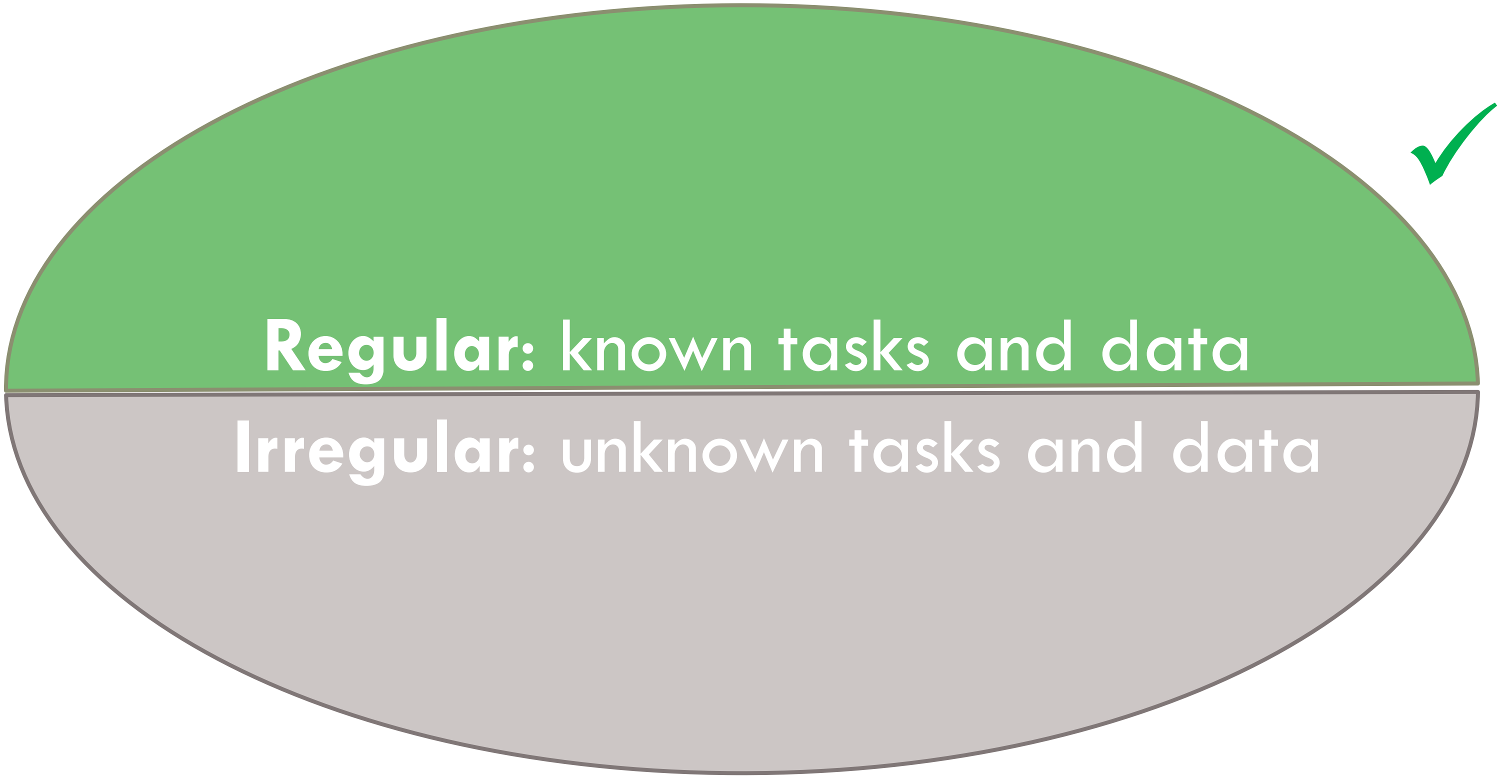

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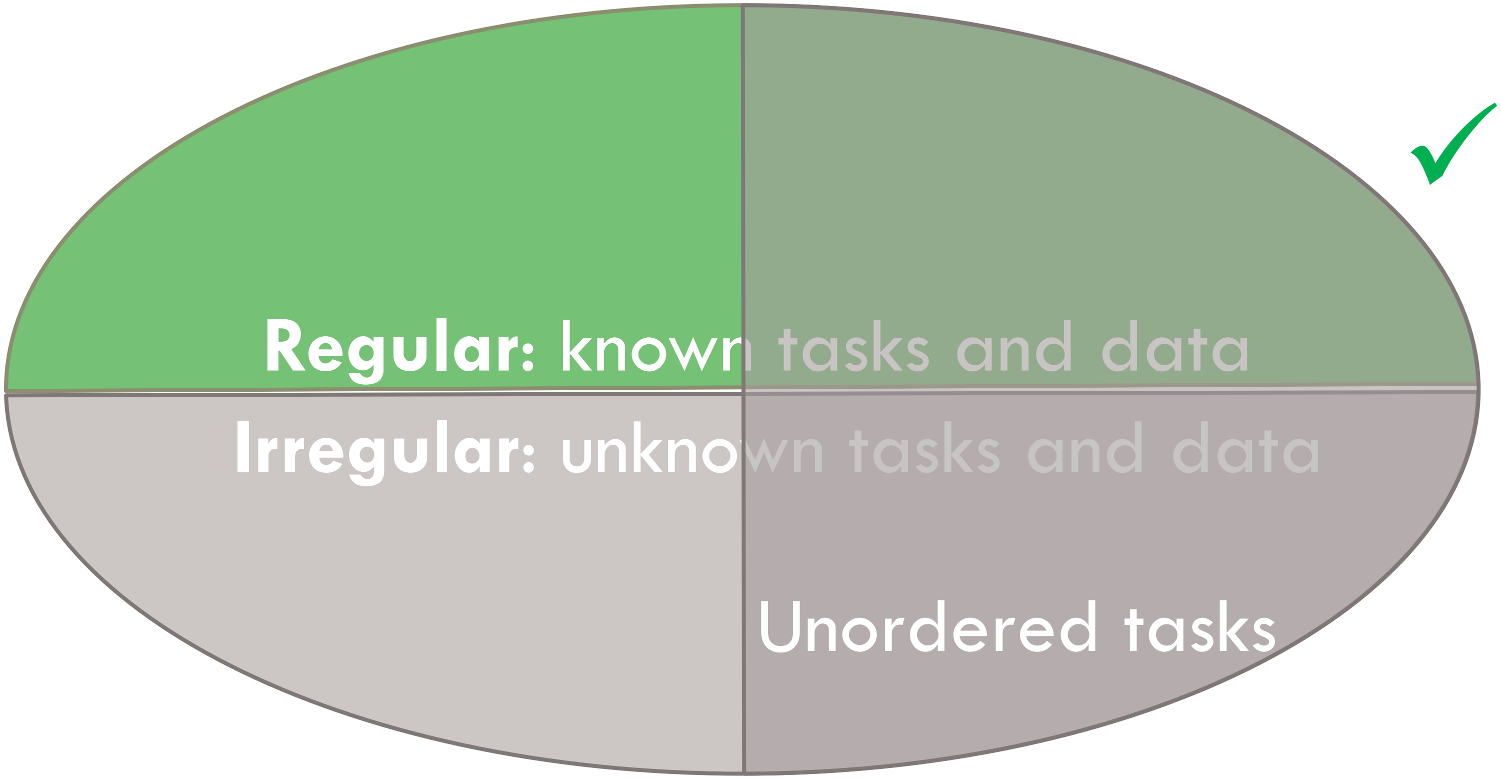

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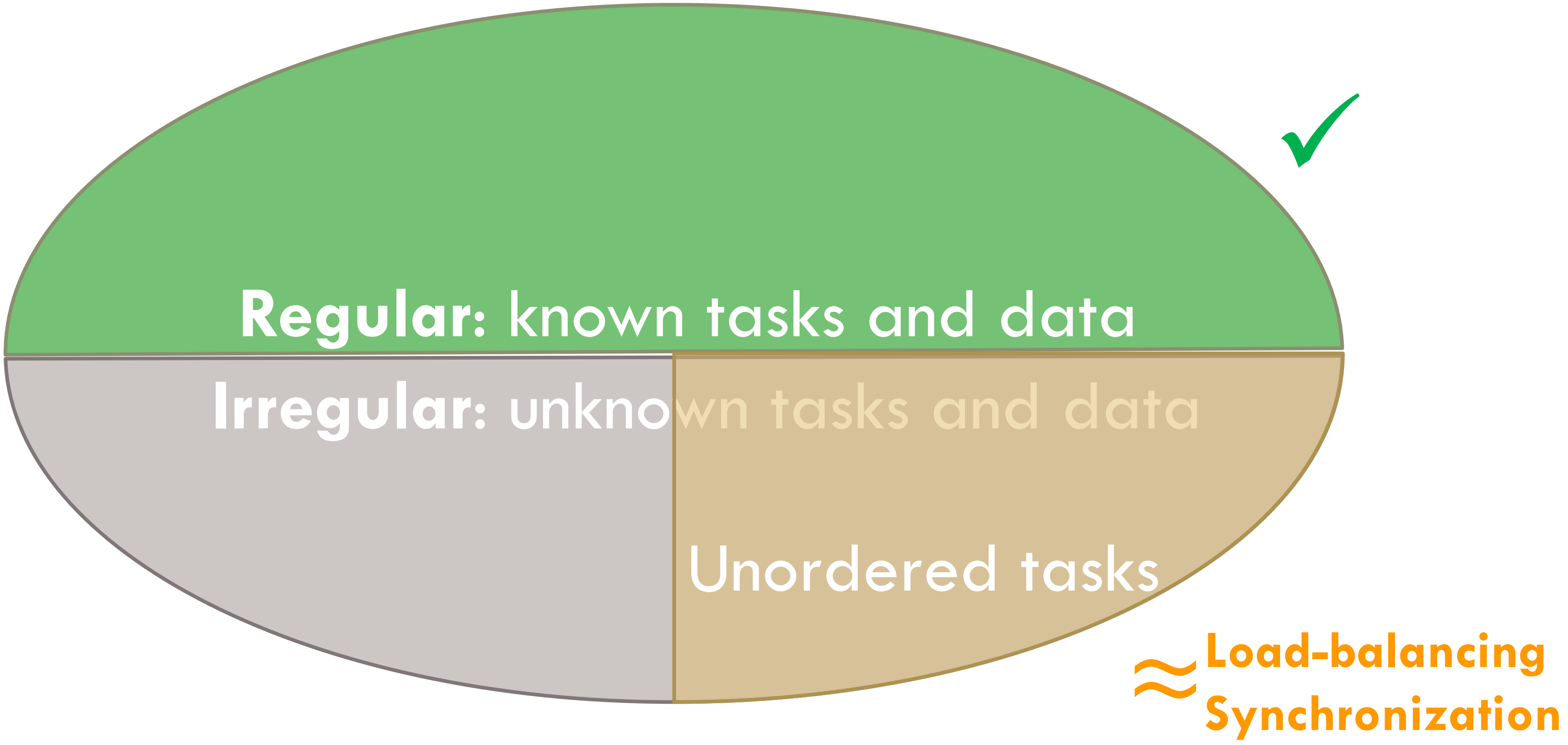

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≈ **Load-balancing**
**Synchronization**

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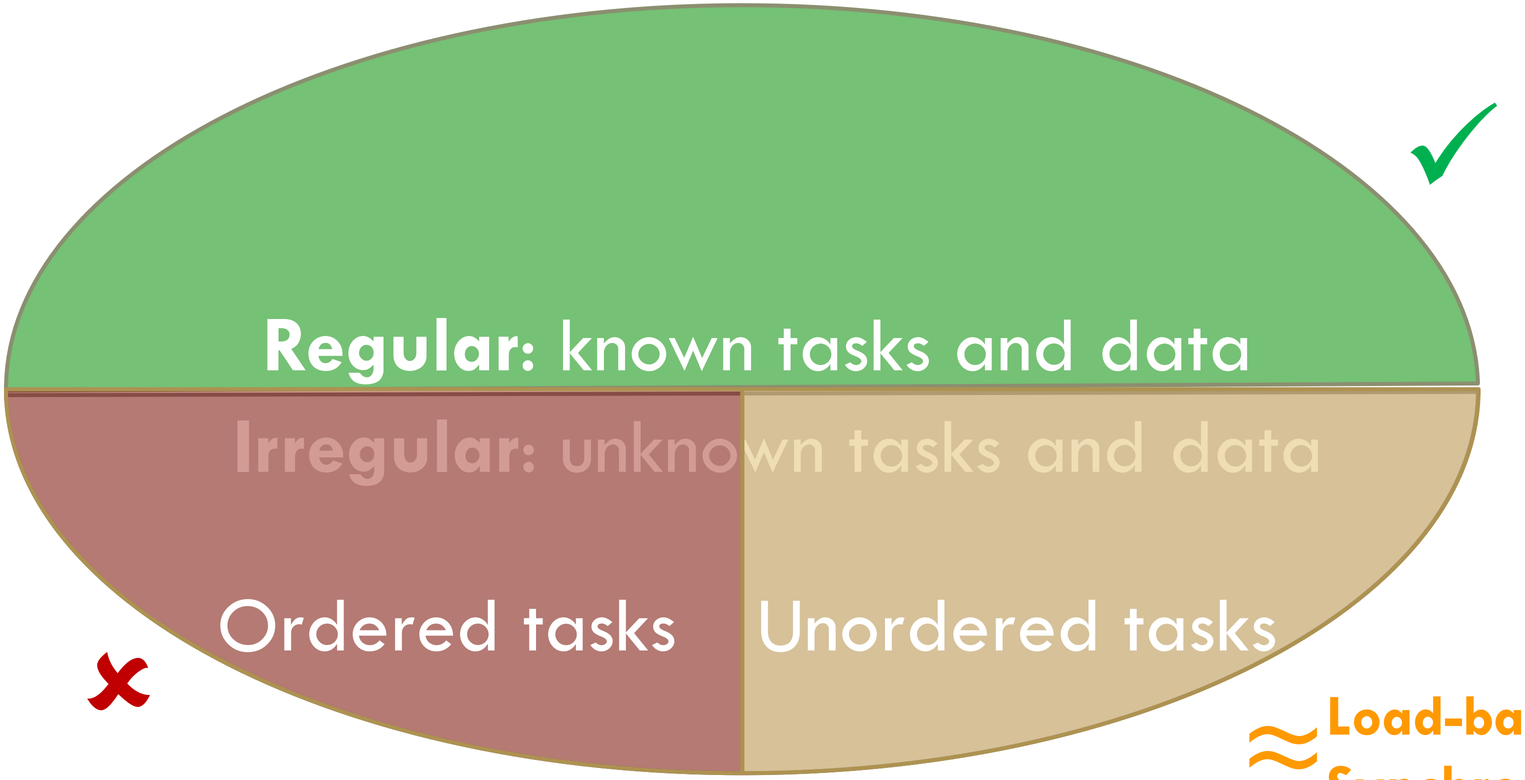

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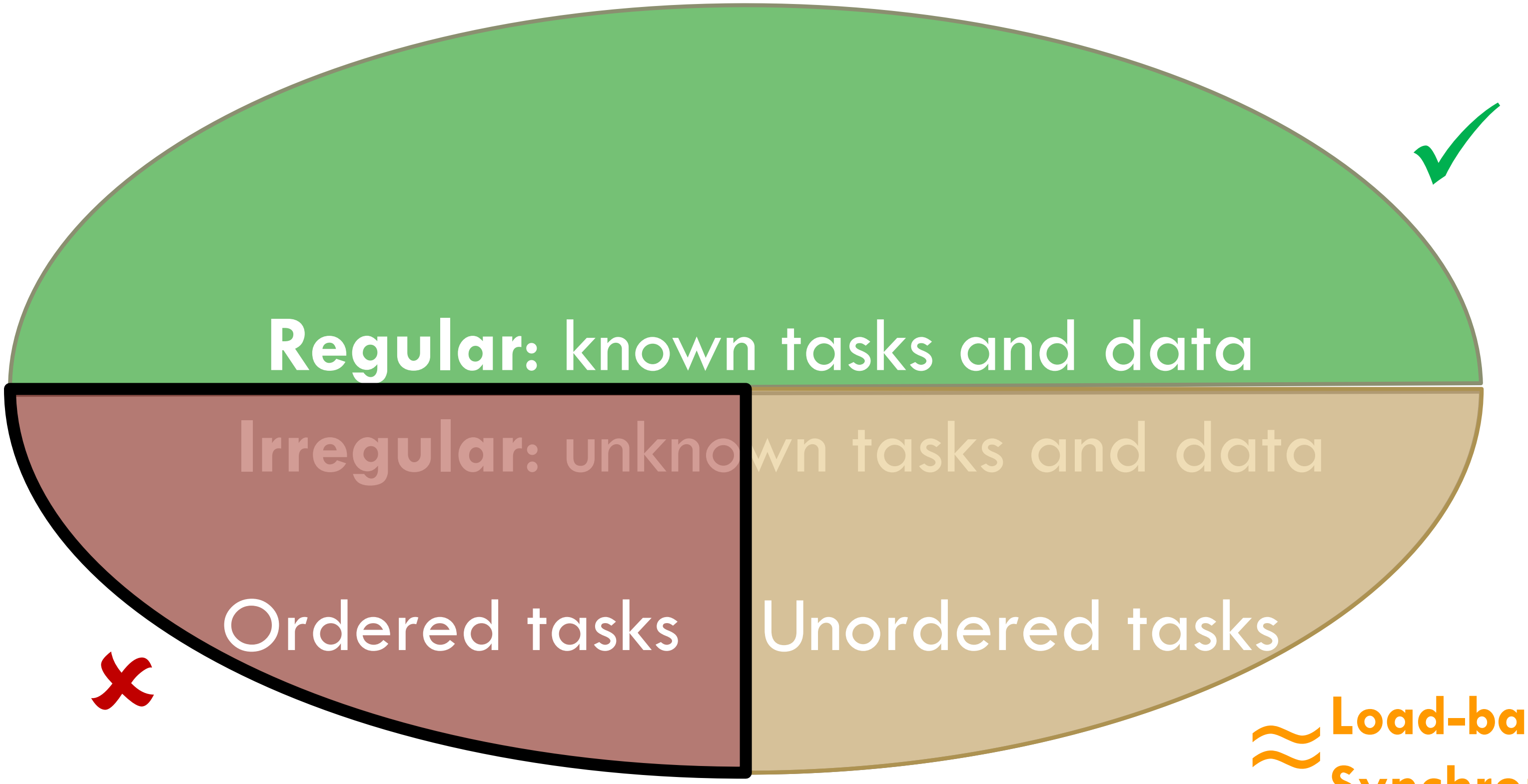

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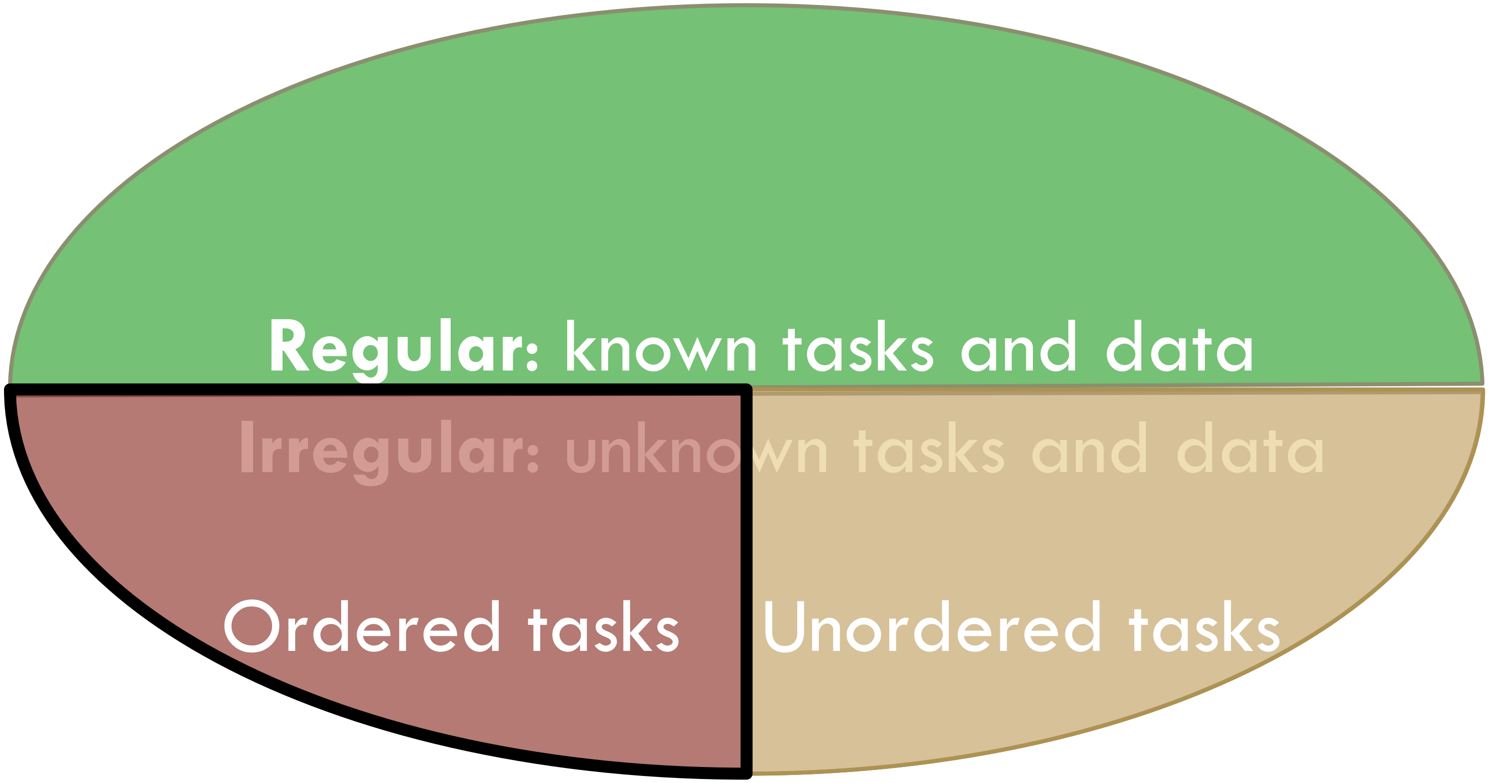
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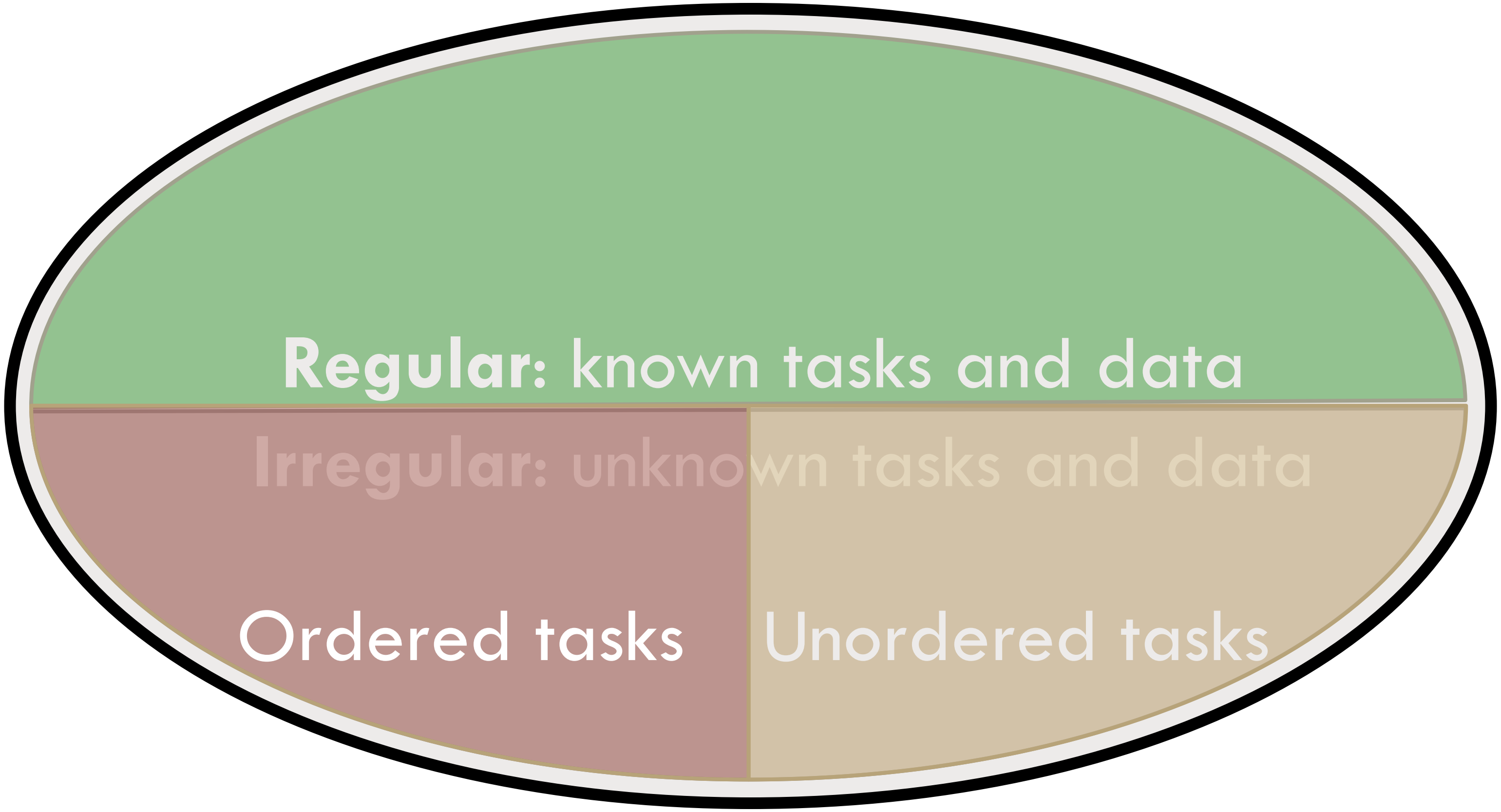
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Ordering is a simple and general form of synchronization

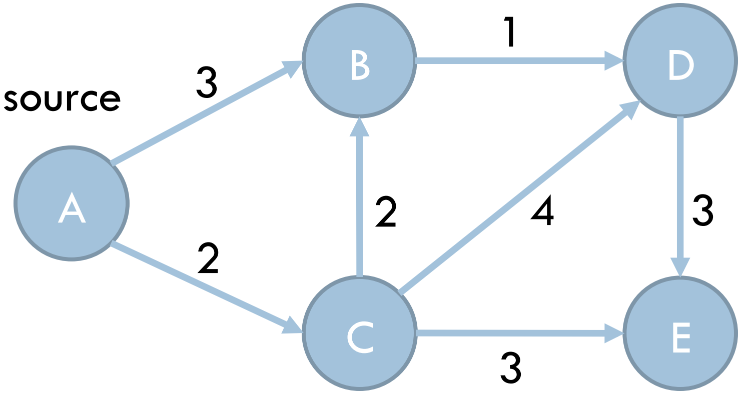
Support for **order** enables widespread parallelism

# Outline

- □ Understanding Ordered Parallelism
- □ Swarm
- □ Evaluation

# Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



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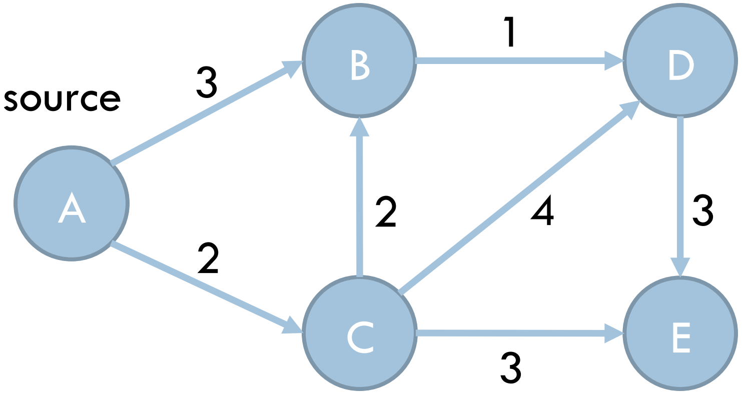

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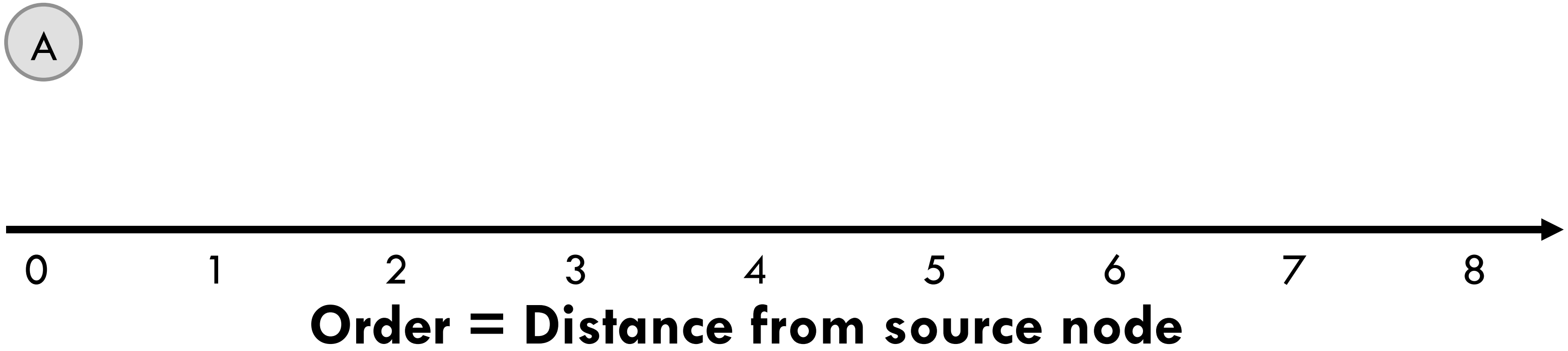

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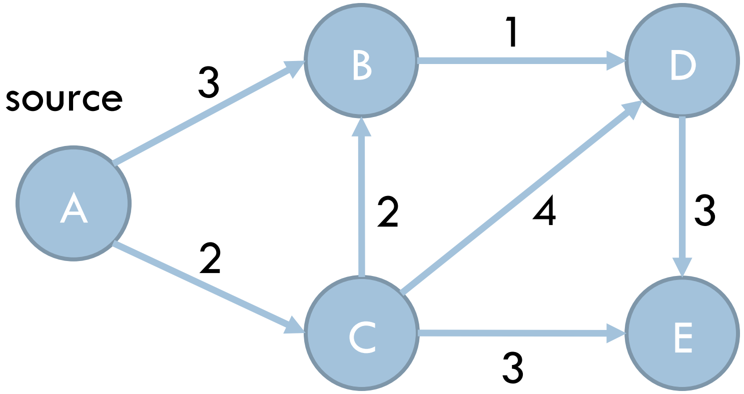

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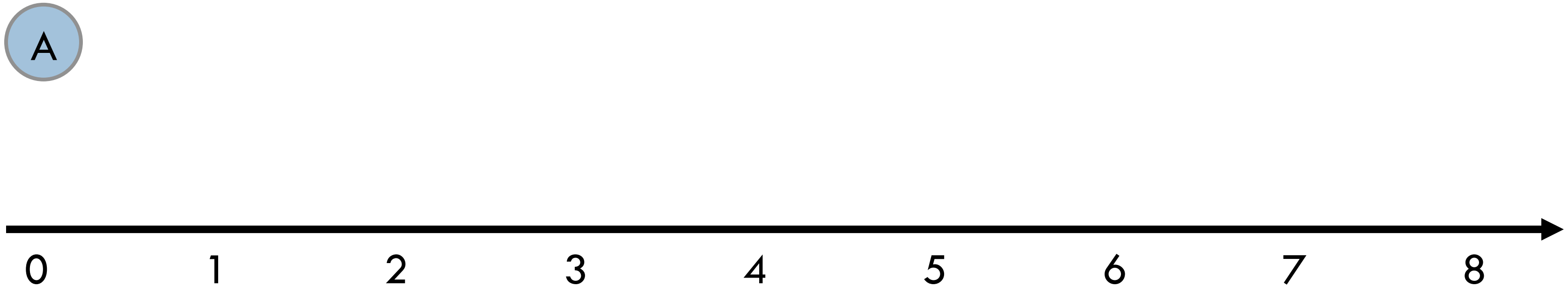

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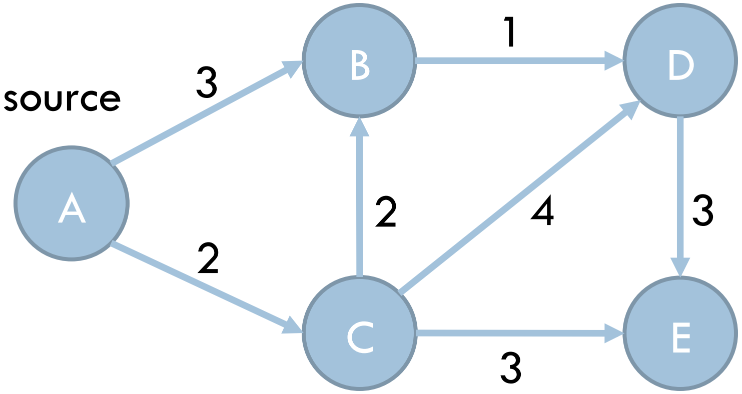

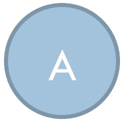

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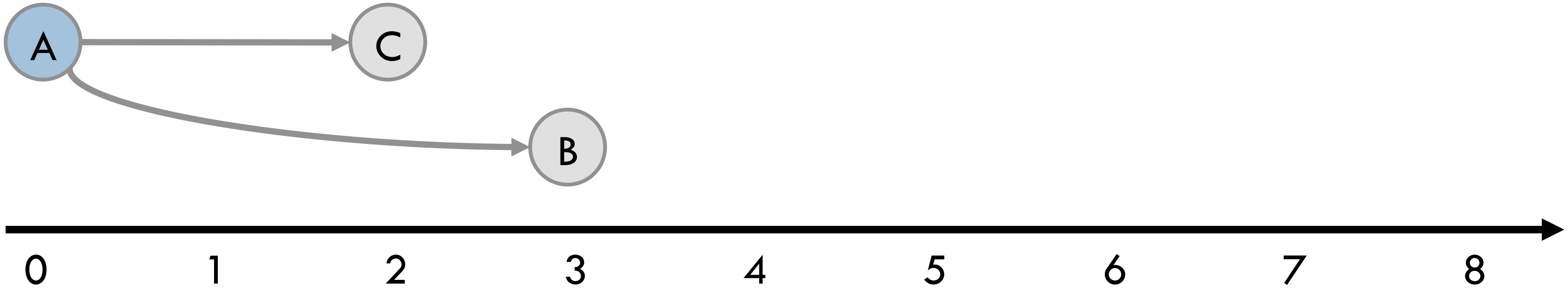

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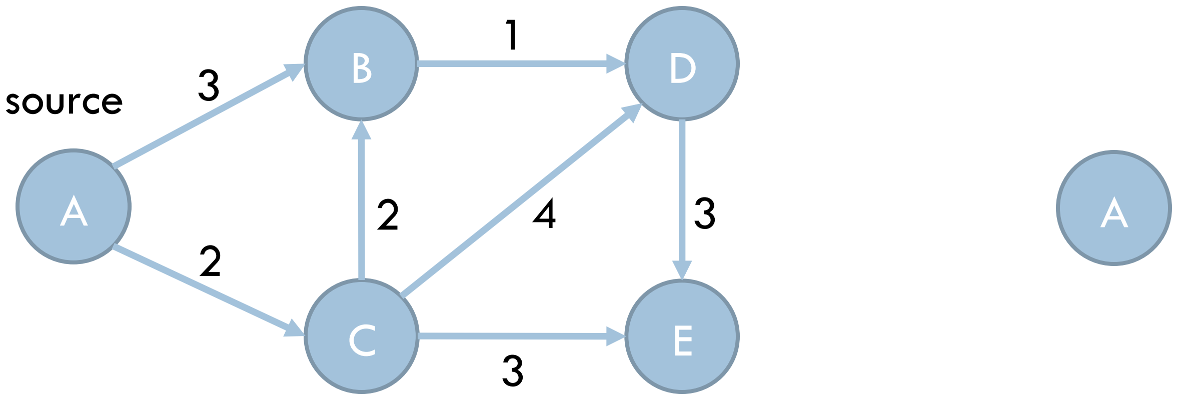

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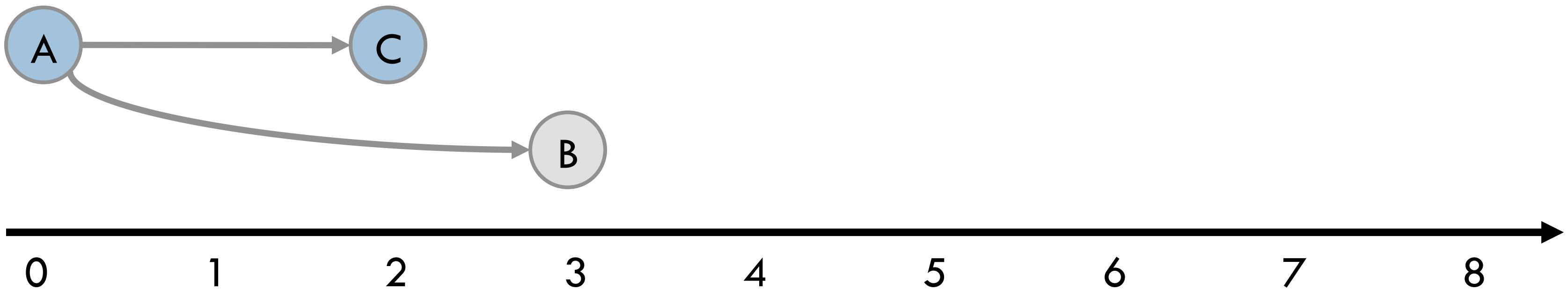

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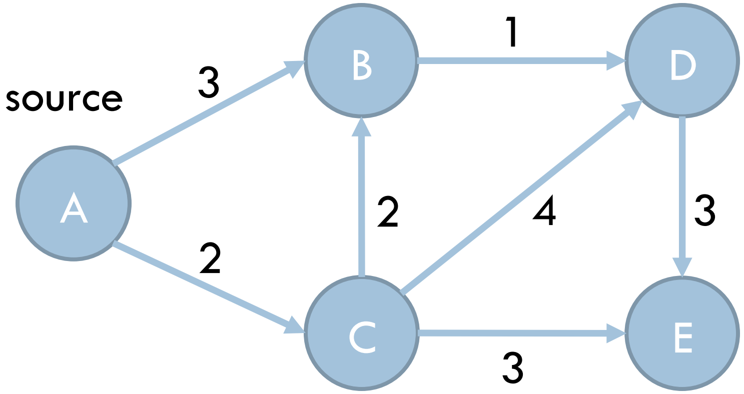

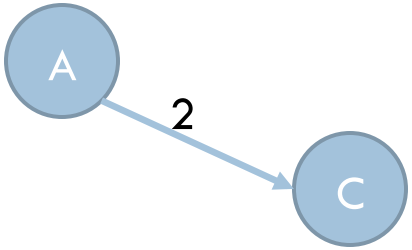

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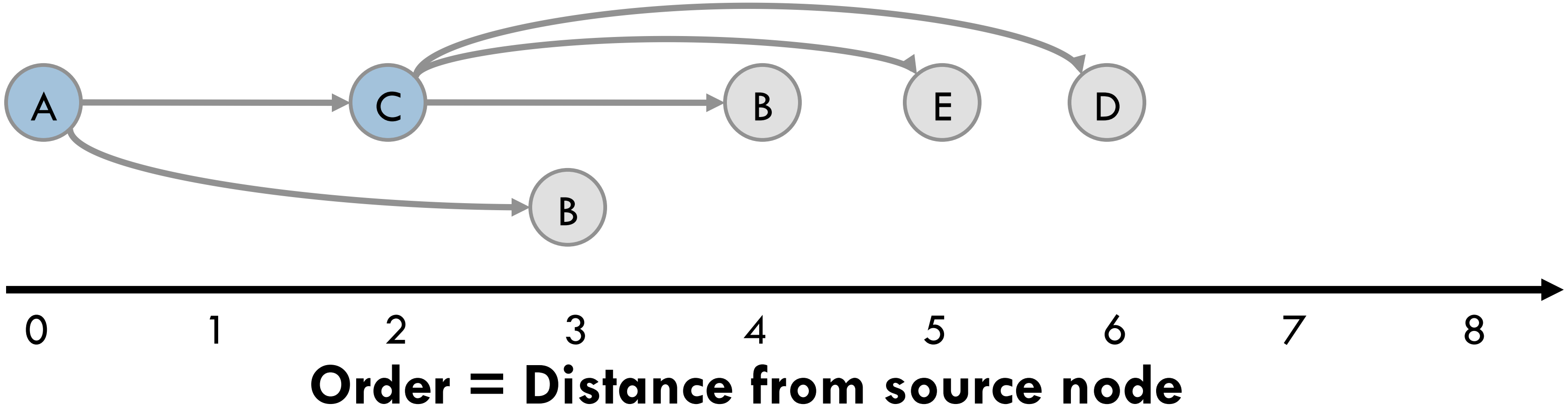

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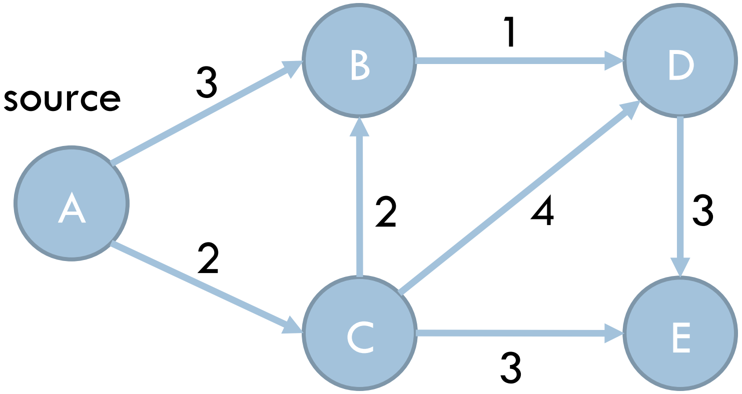

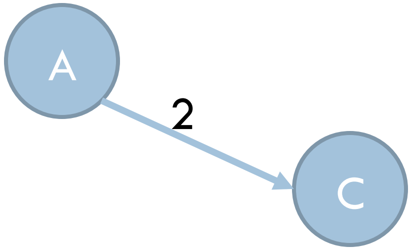

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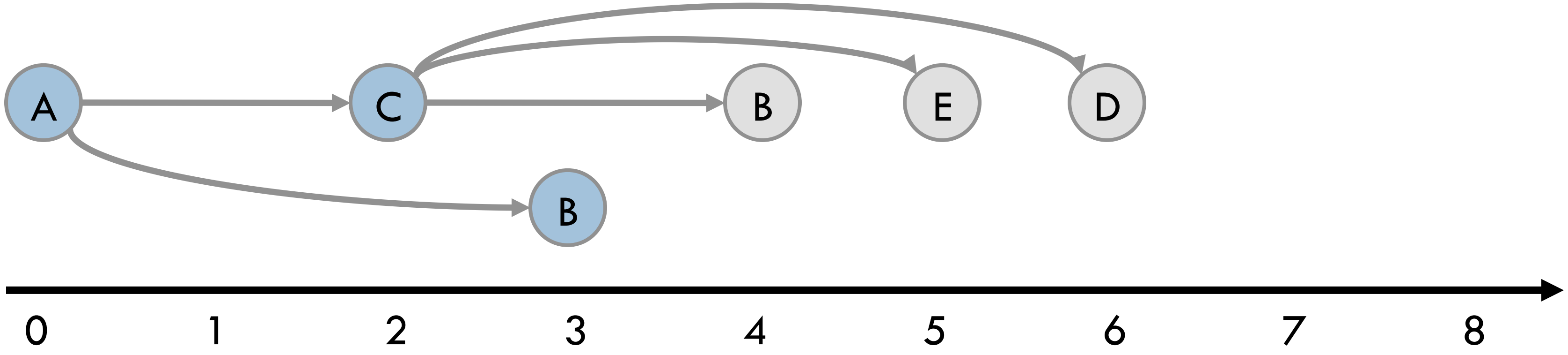

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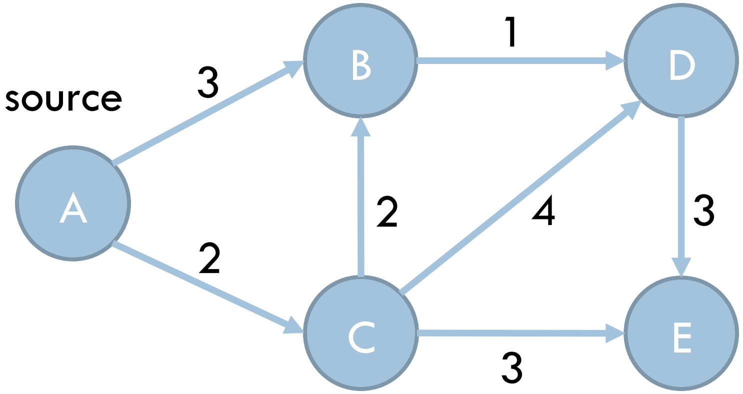

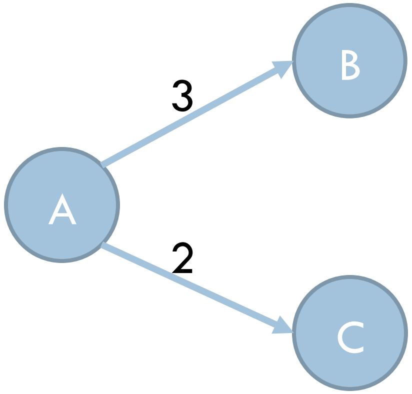

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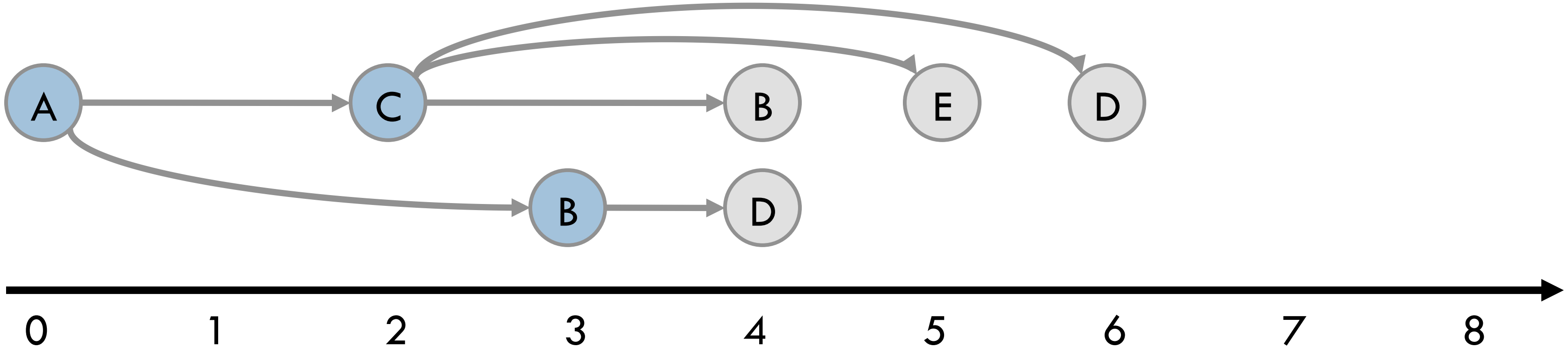

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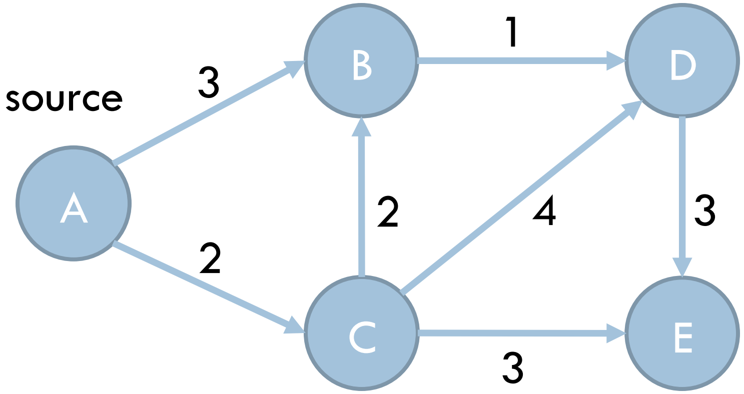

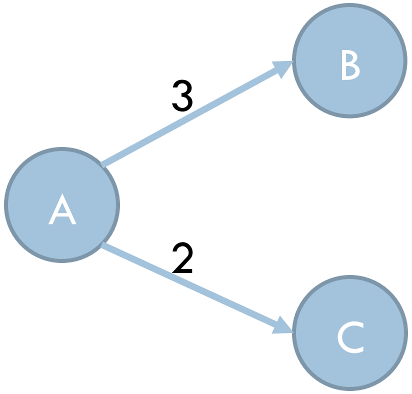

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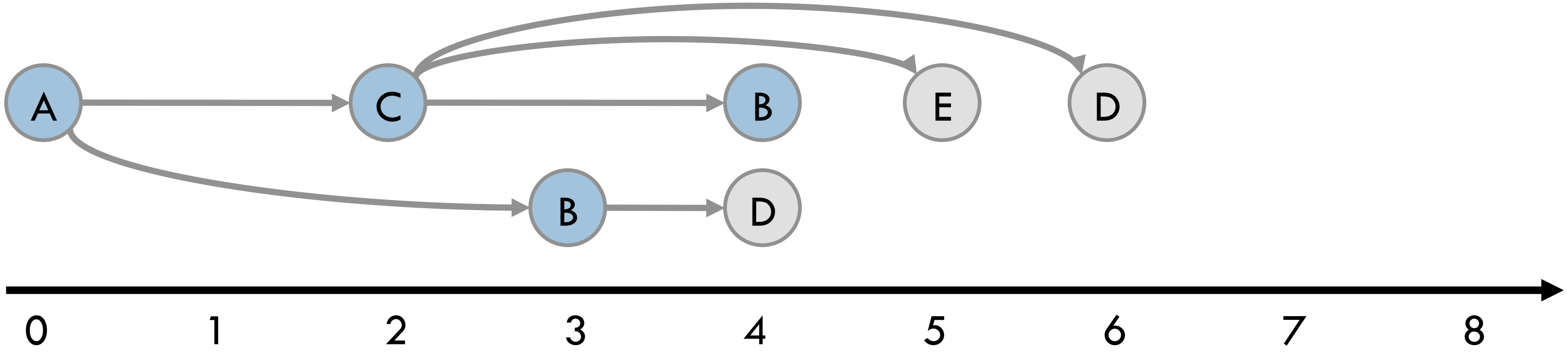

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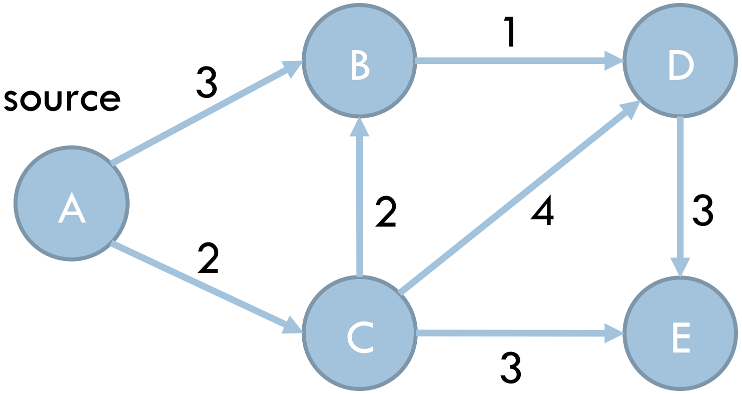

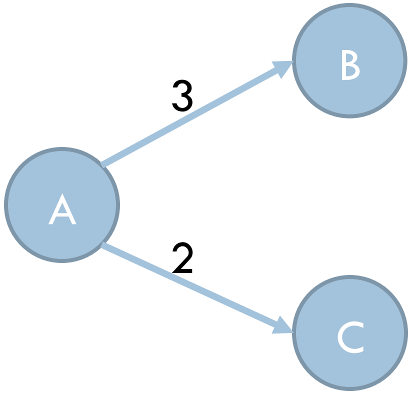

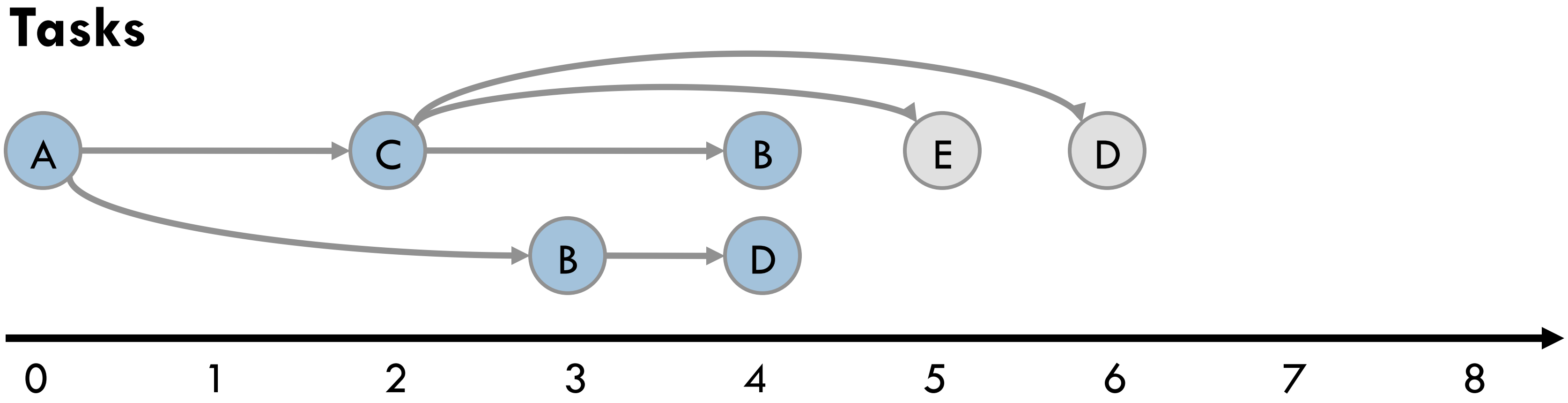

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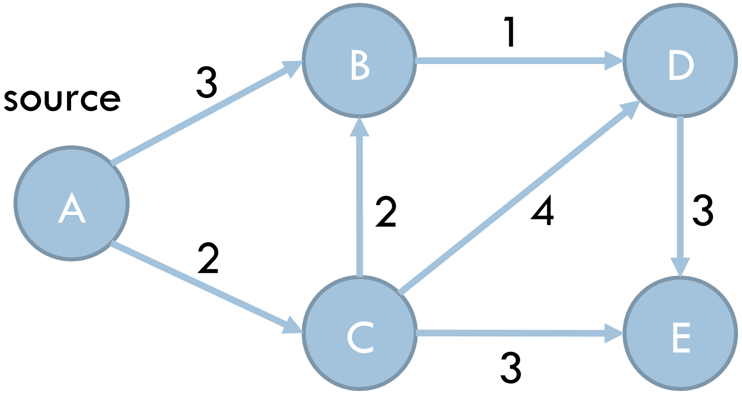

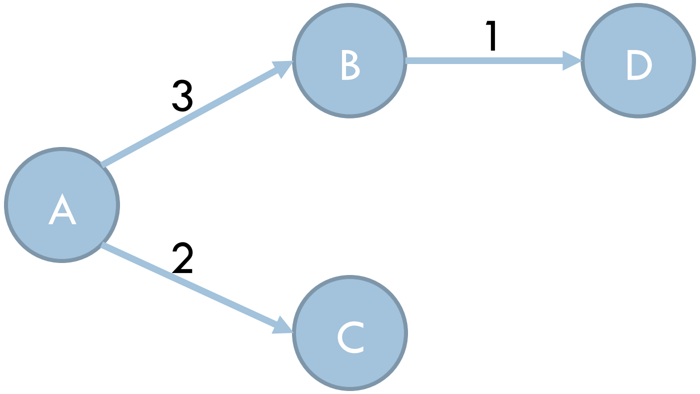

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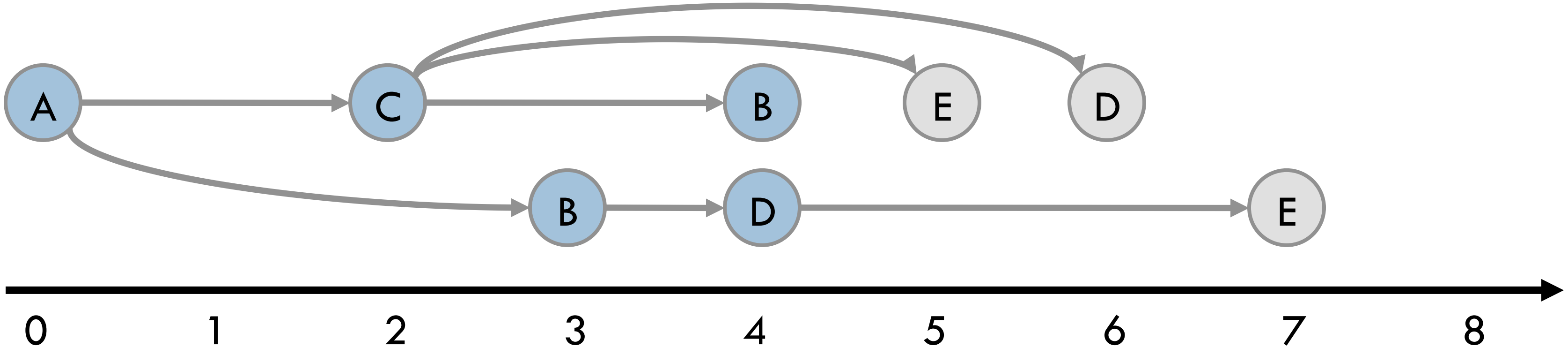

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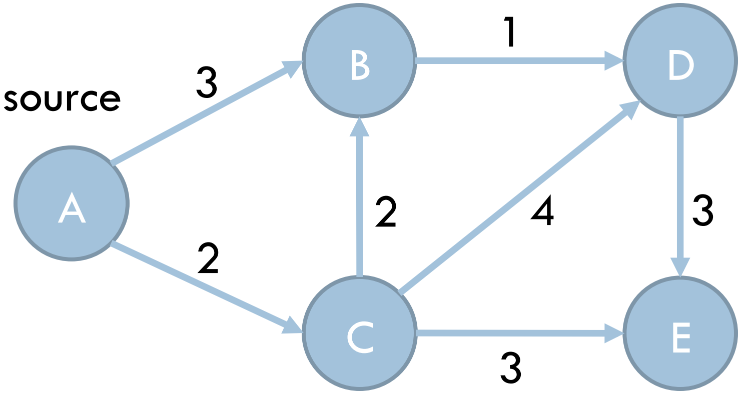

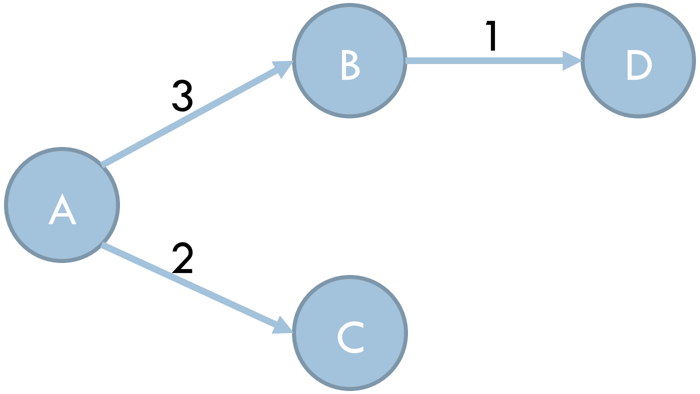

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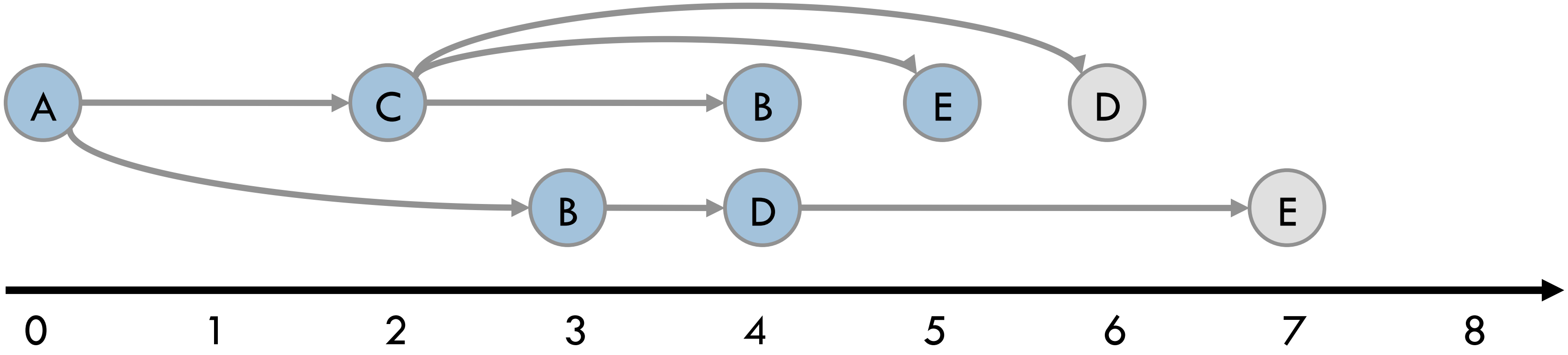

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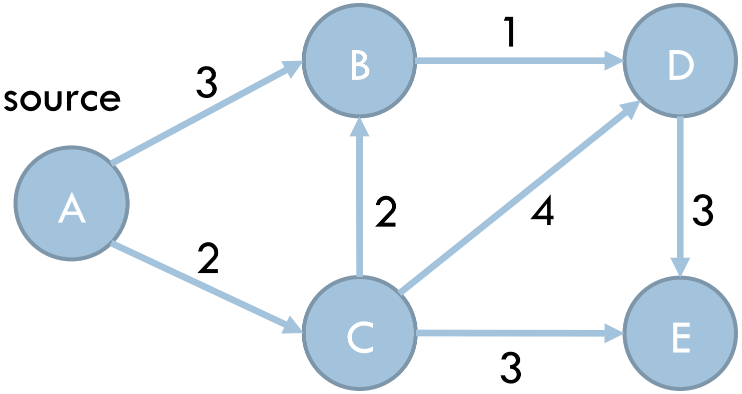

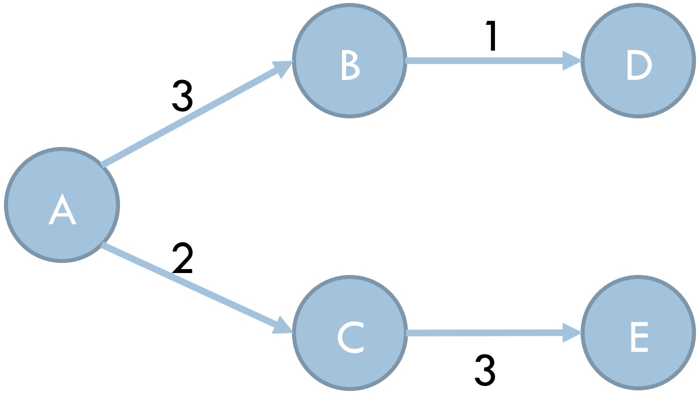

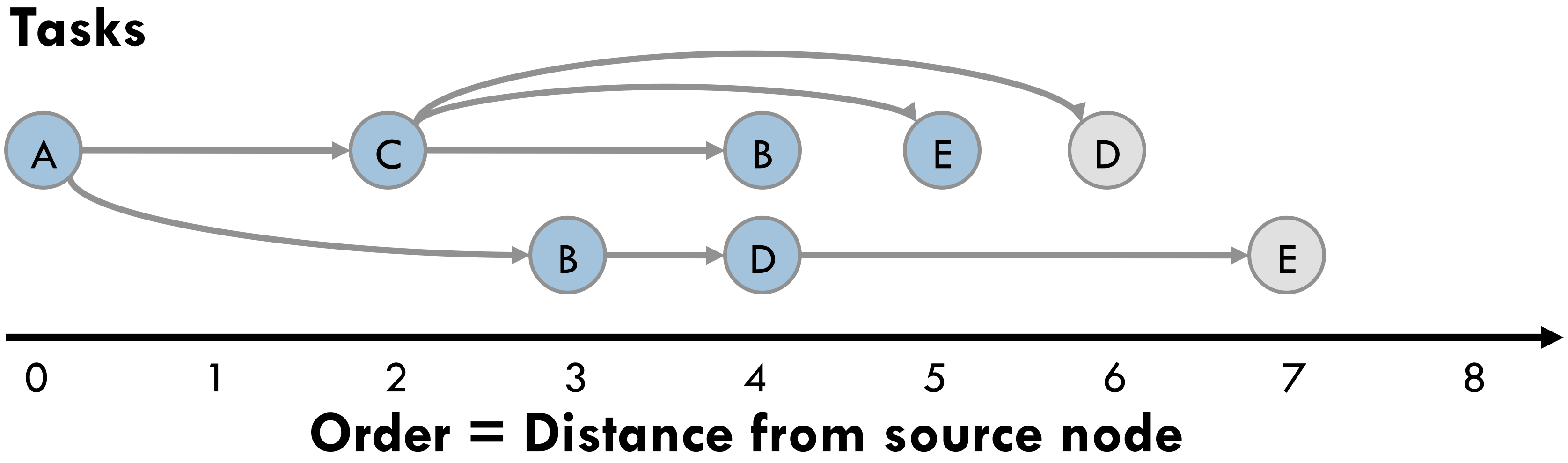

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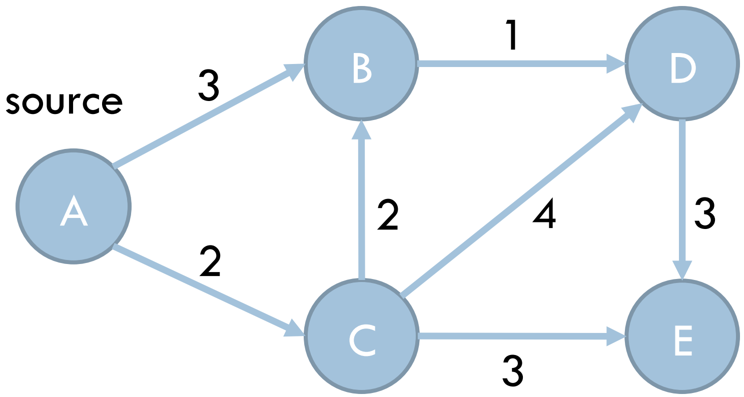

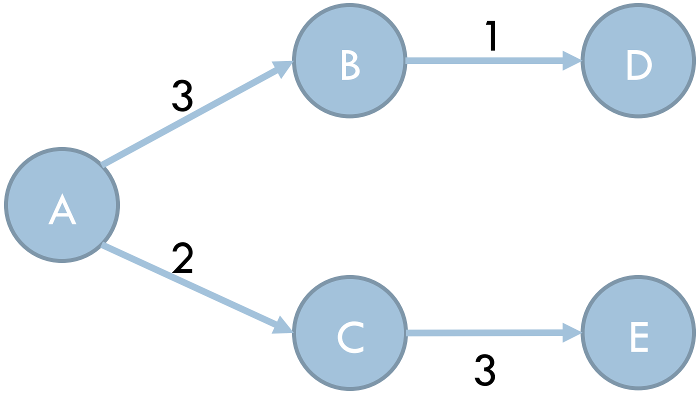

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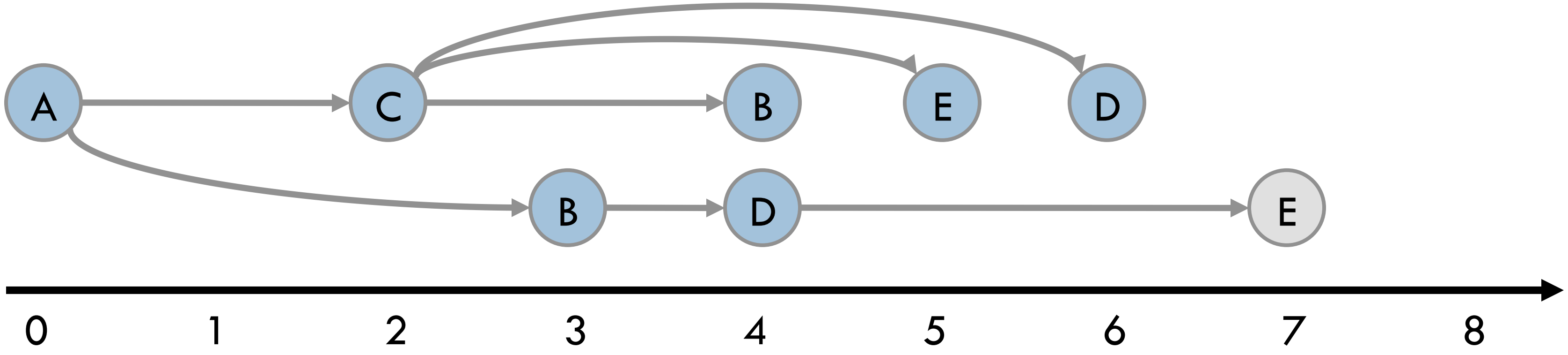

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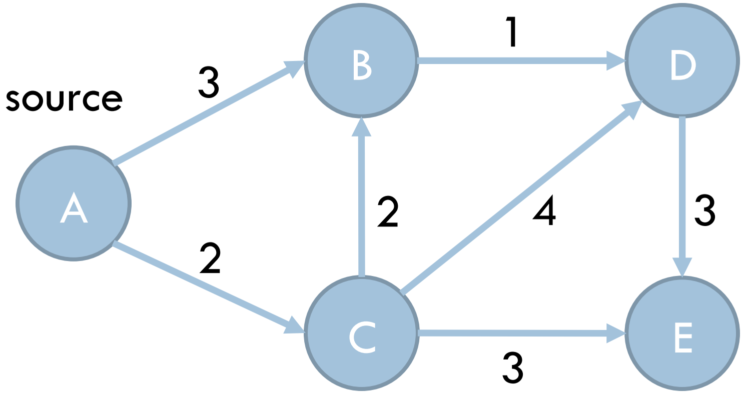

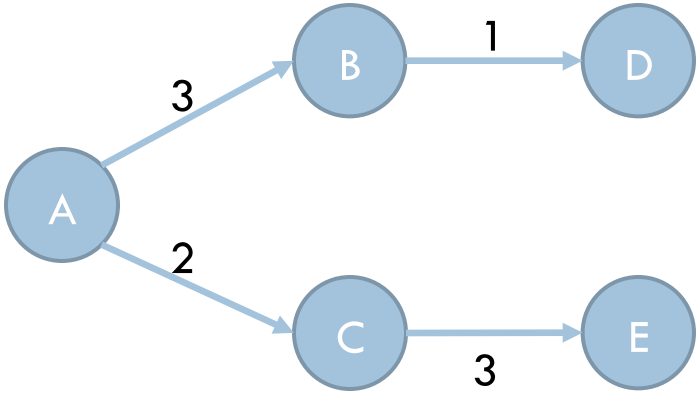

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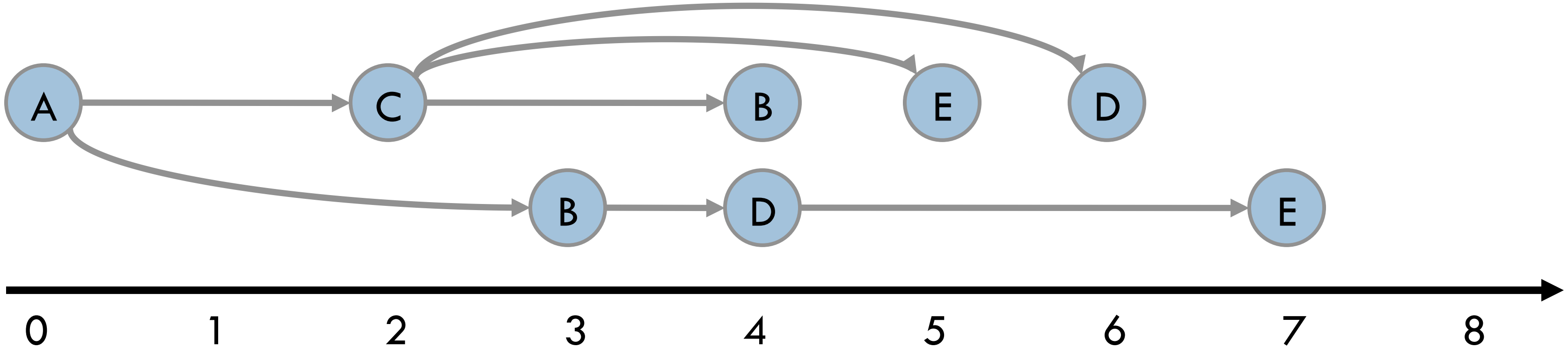

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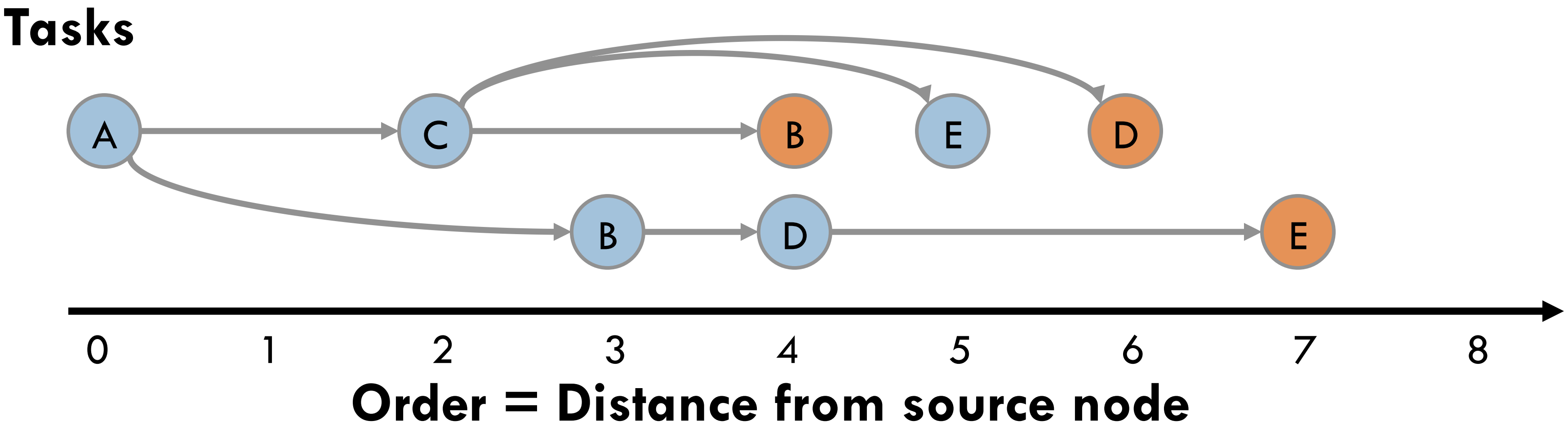

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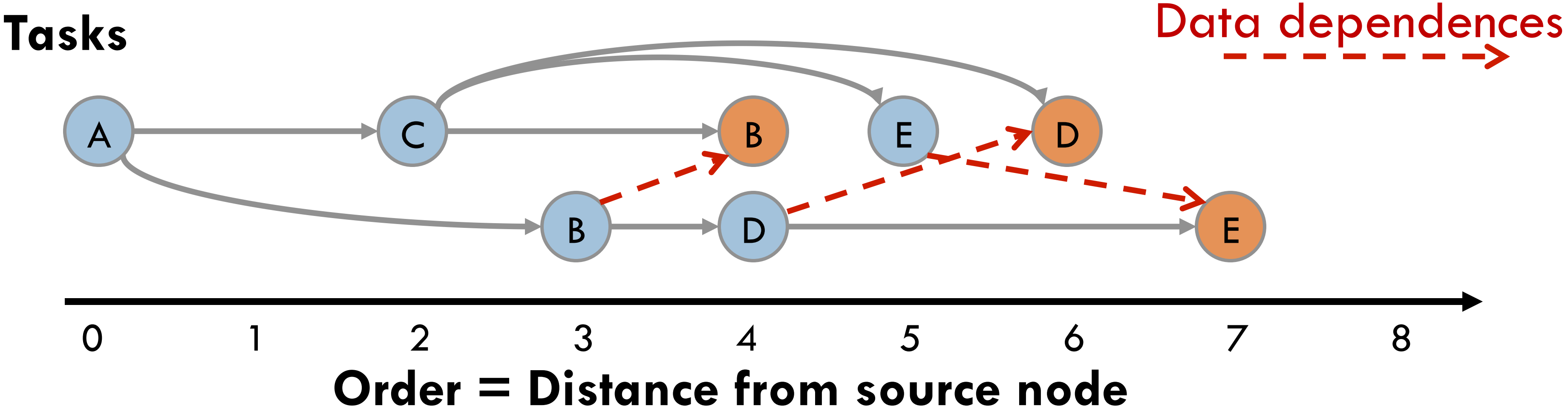

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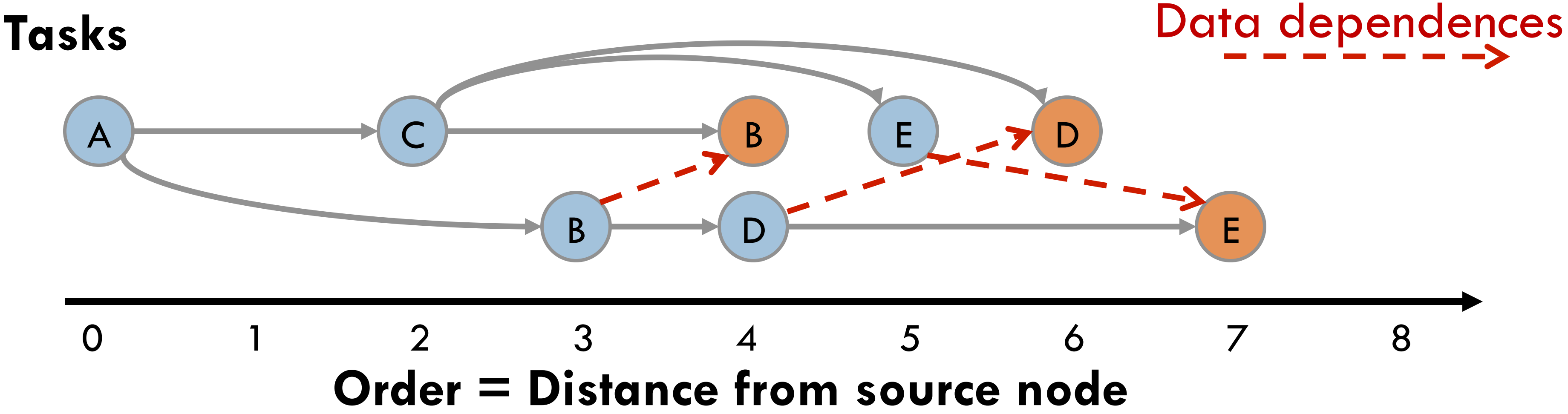

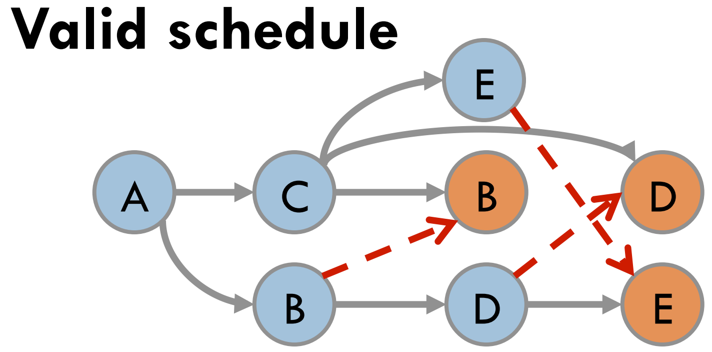

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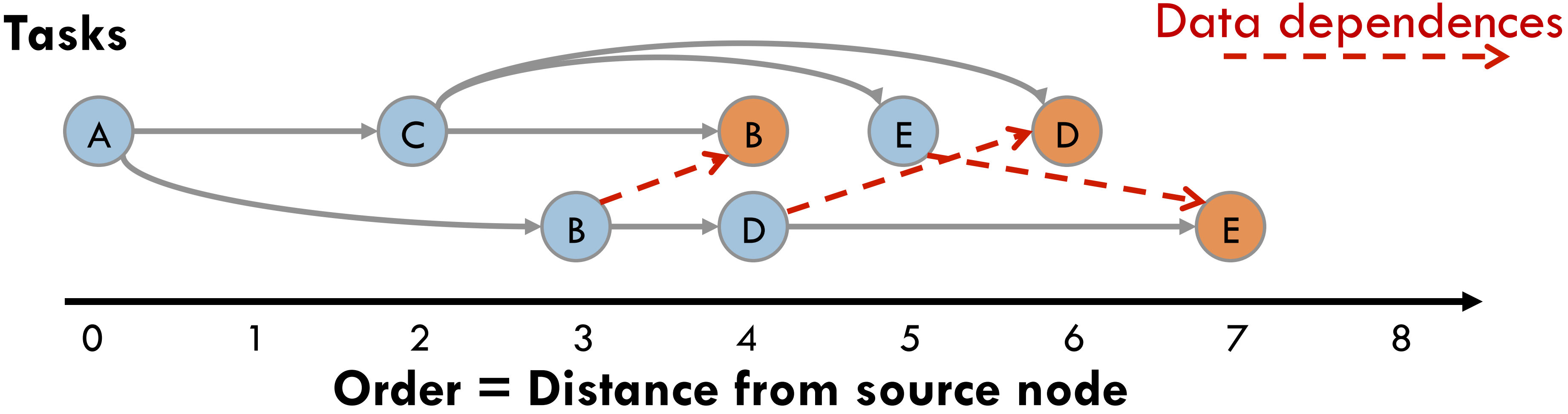

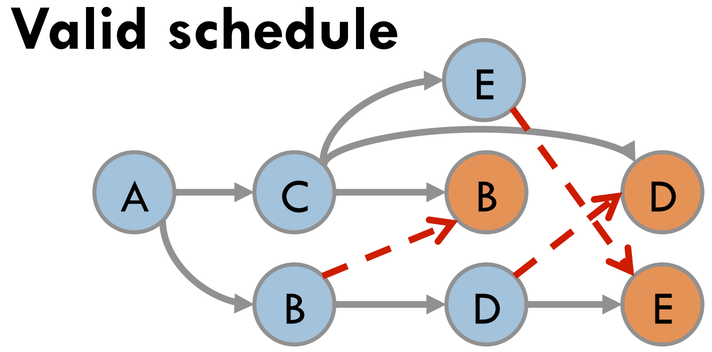

2x parallelism (more in larger graphs)

Tasks and dependences unknown in advance

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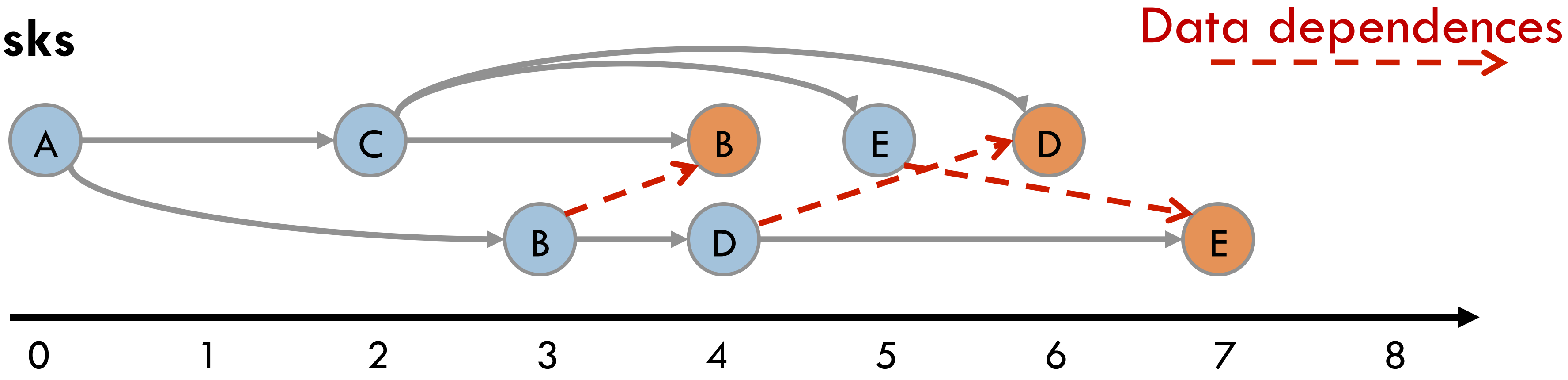

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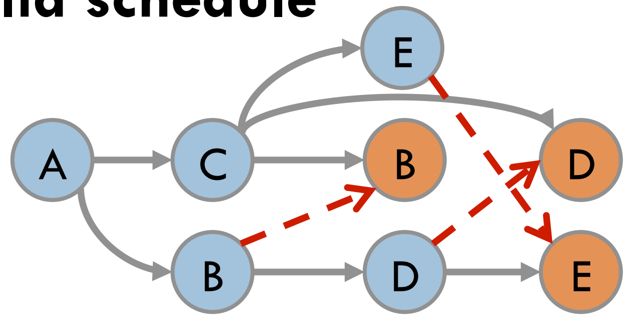
**Valid schedule**



**2x parallelism**
**(more in larger graphs)**

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Need speculative execution to elide order constraints

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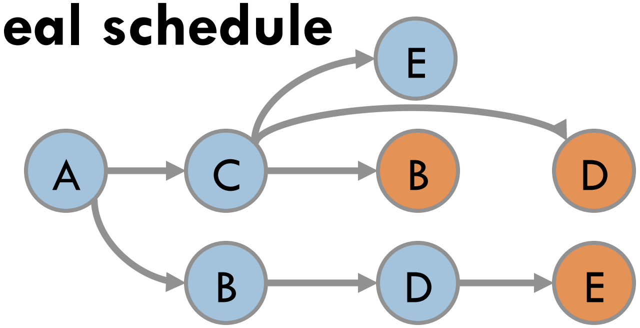

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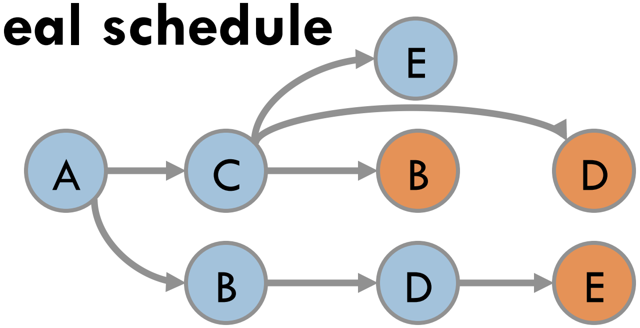

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| | |
|---|---|
| max | 800x |

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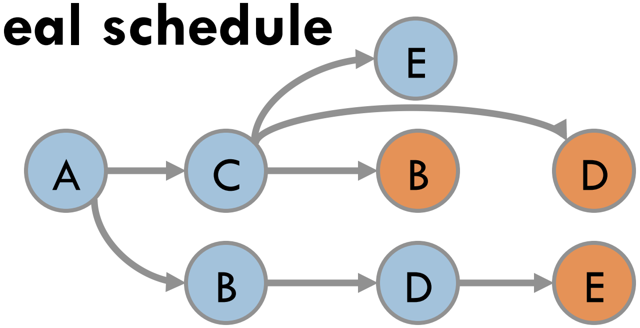

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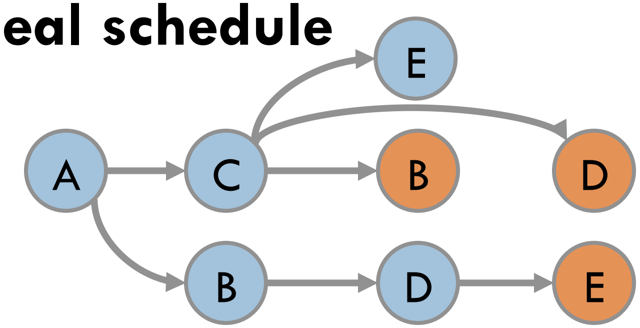

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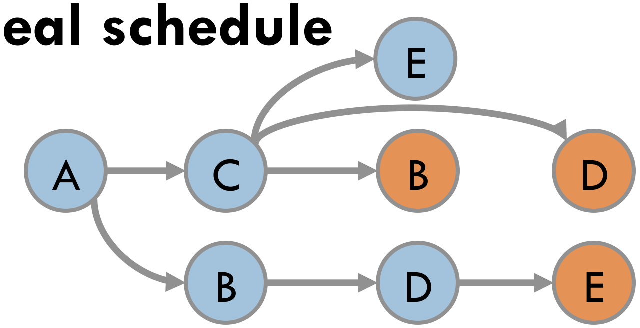

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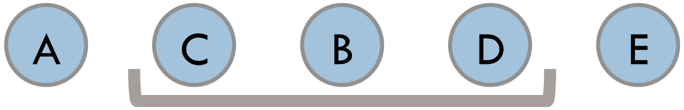

*N*-task window

Can execute *N* tasks ahead of the earliest active task

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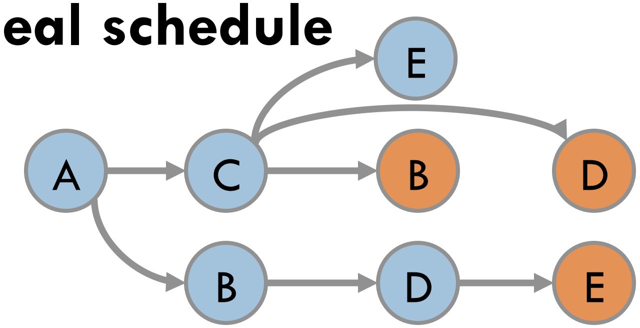

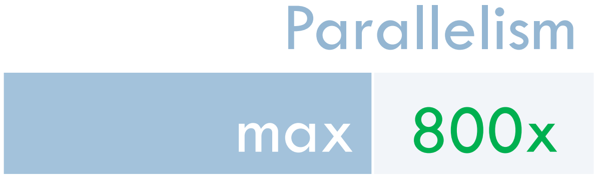

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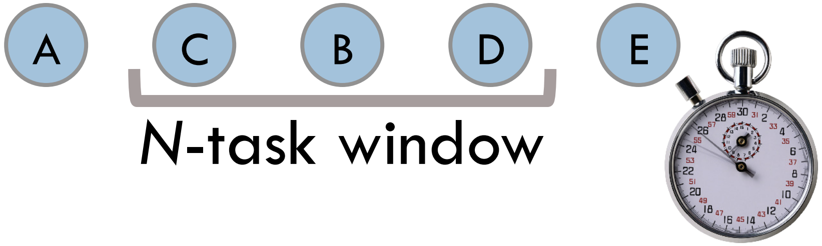

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# Insights about Ordered Parallelism

## 1. With perfect speculation, parallelism is plentiful

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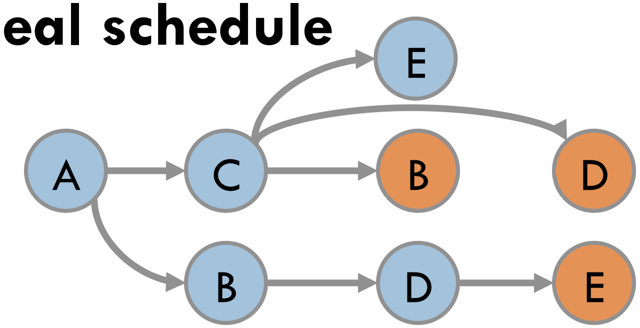

| | Parallelism |
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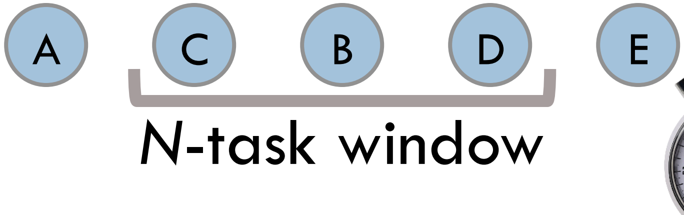

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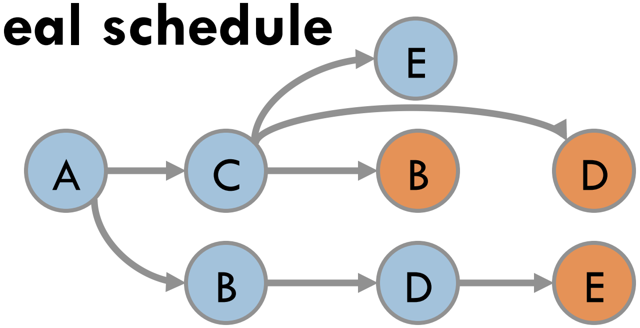

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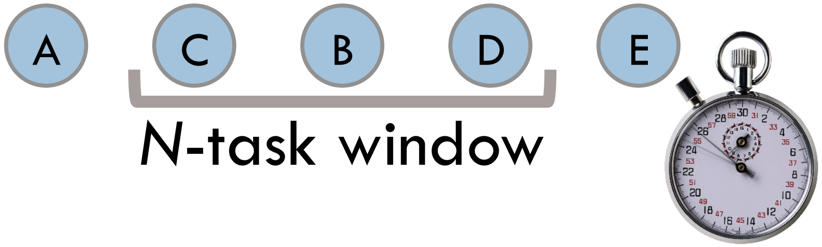

*N*-task window

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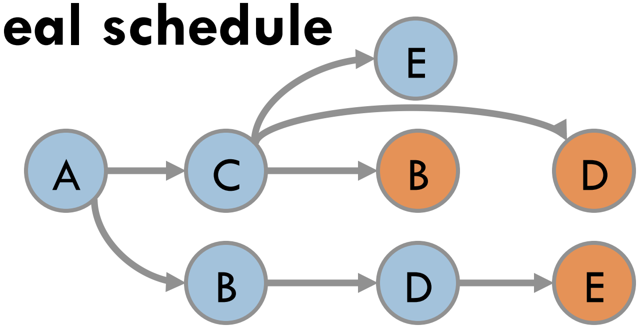

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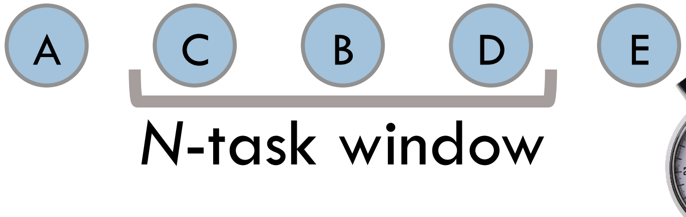

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**Need a large window of speculation**

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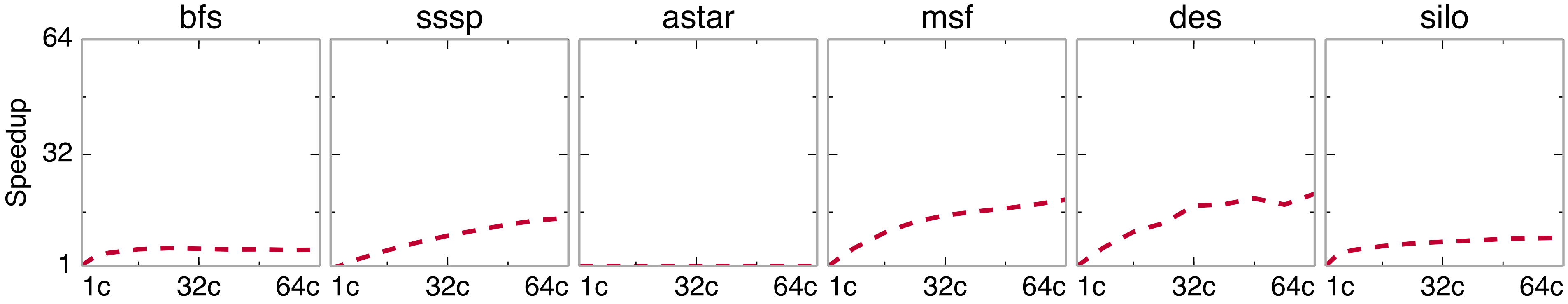

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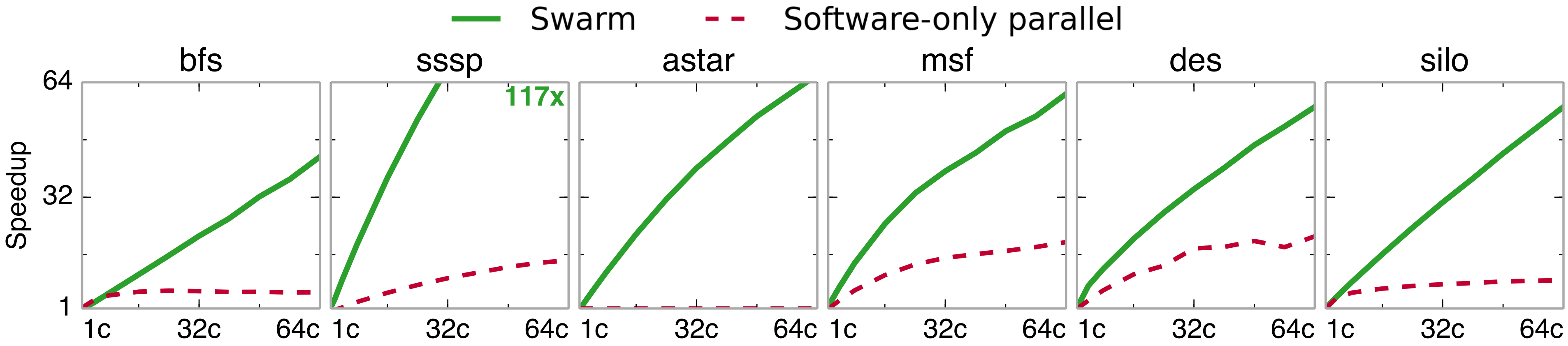

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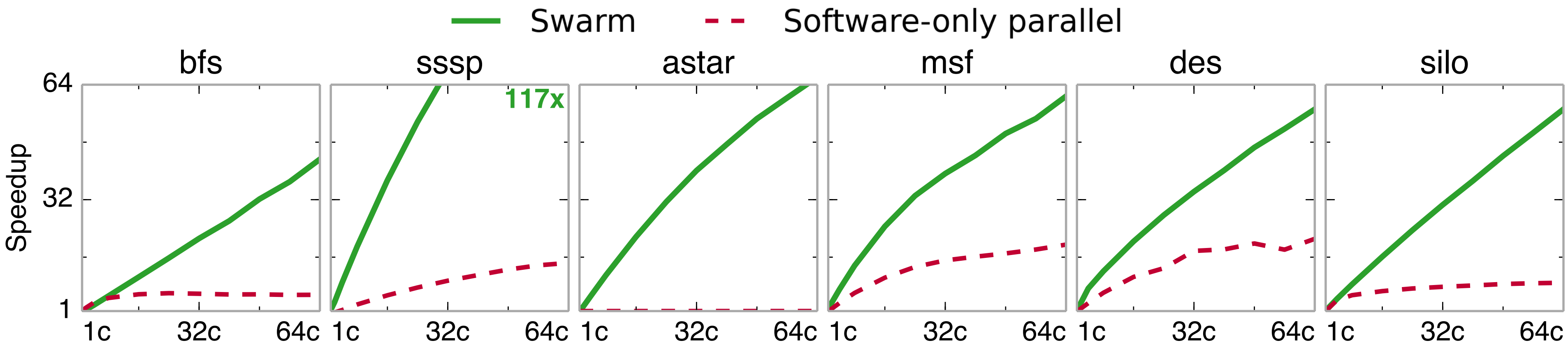

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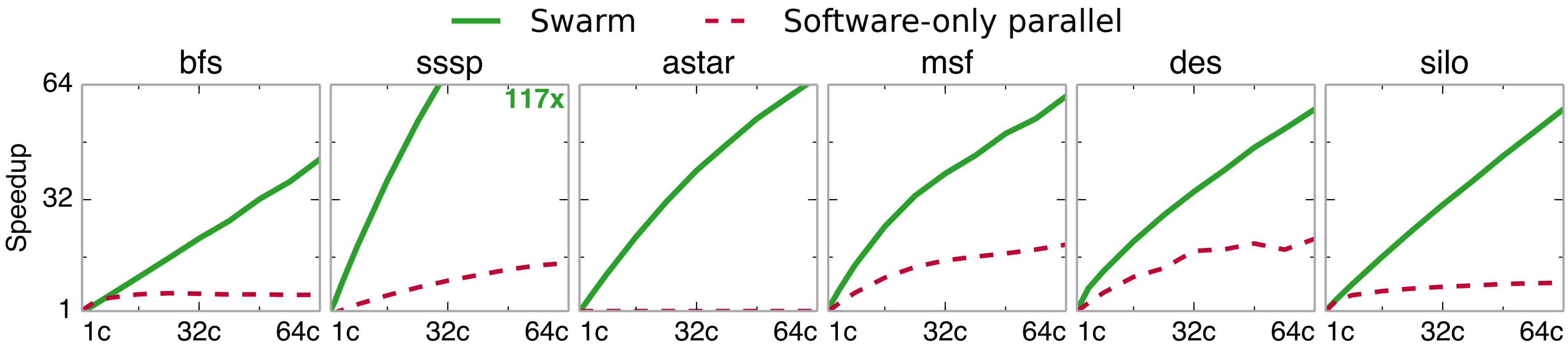

□ Execution model based on timestamped tasks

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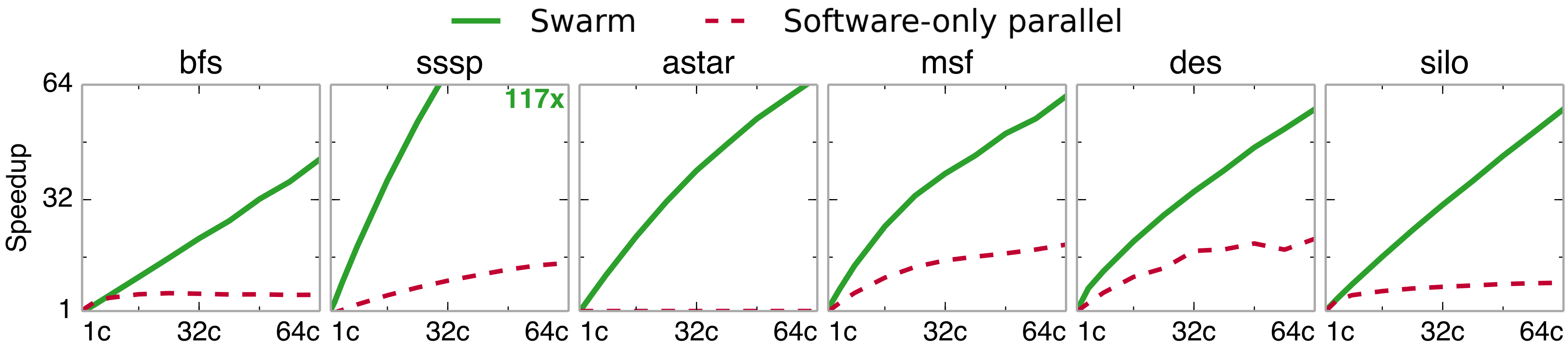

- Execution model based on timestamped tasks
- Architecture executes tasks speculatively out of order
  - Leverages execution model to scale

# Outline

- □ Understanding Ordered Parallelism
- □ Swarm
- □ Evaluation

# Swarm Execution Model

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swarm::enqueue(fptr, ts, args...);
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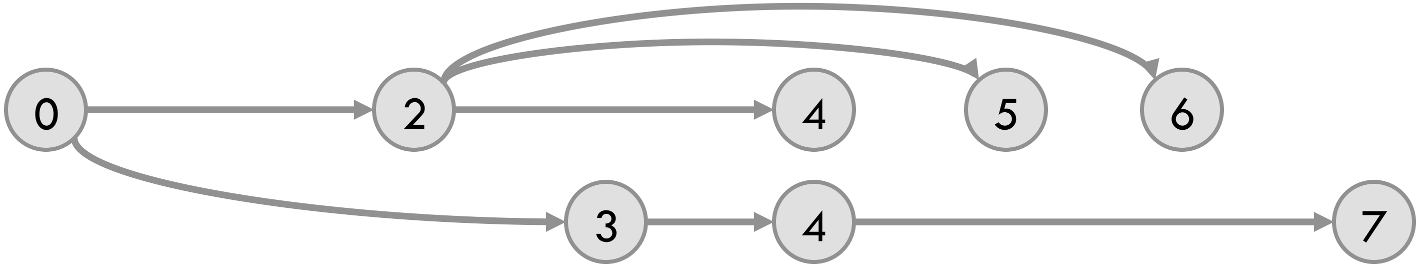

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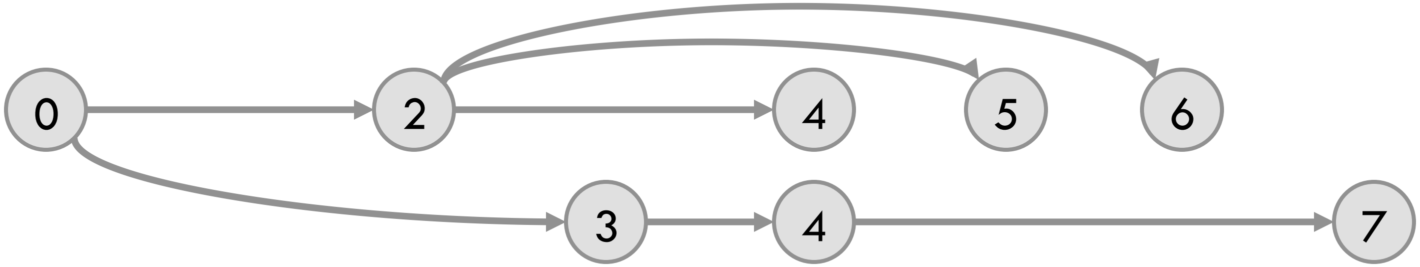

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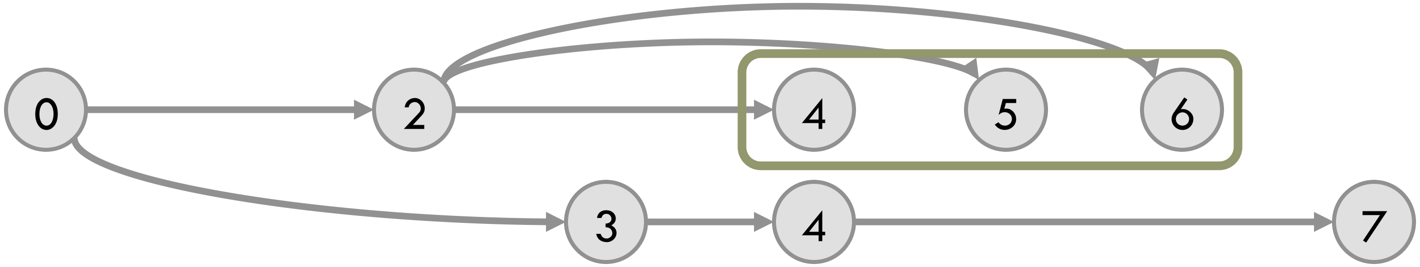

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# Swarm Task Example: Dijkstra

```
void ssspTask(Timestamp dist, Vertex& v) {
  if (!v.isVisited()) {
    v.distance = dist;
    for (Vertex& u : v.neighbors) {
       Timestamp uDist = dist + edgeWeight(v, u);
       swarm::enqueue(&ssspTask, uDist, u);
    }
  }
}
```

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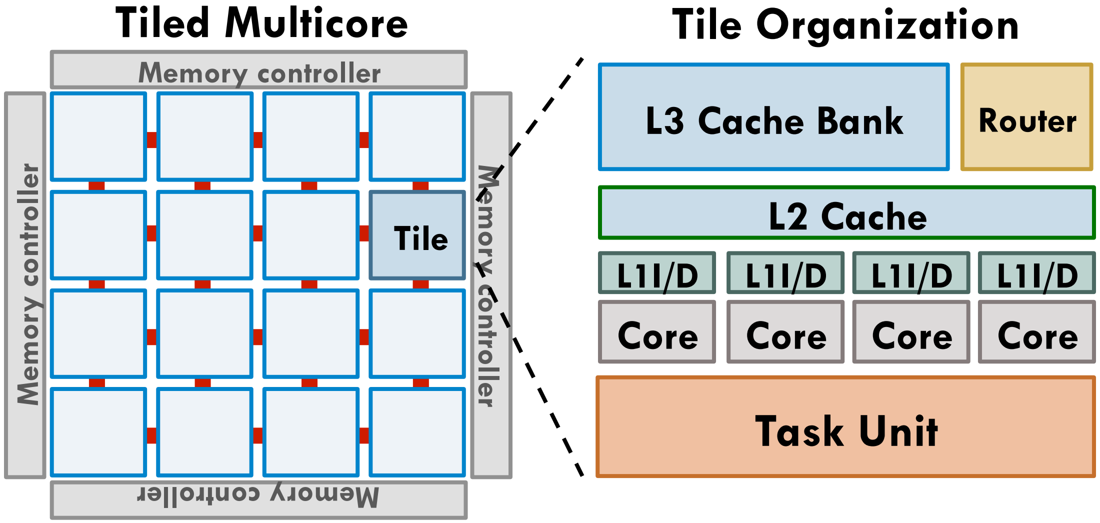
**Timestamp**

```
swarm::enqueue(ssspTask, 0, sourceVertex);
swarm::run();
```

# Swarm Architecture Overview



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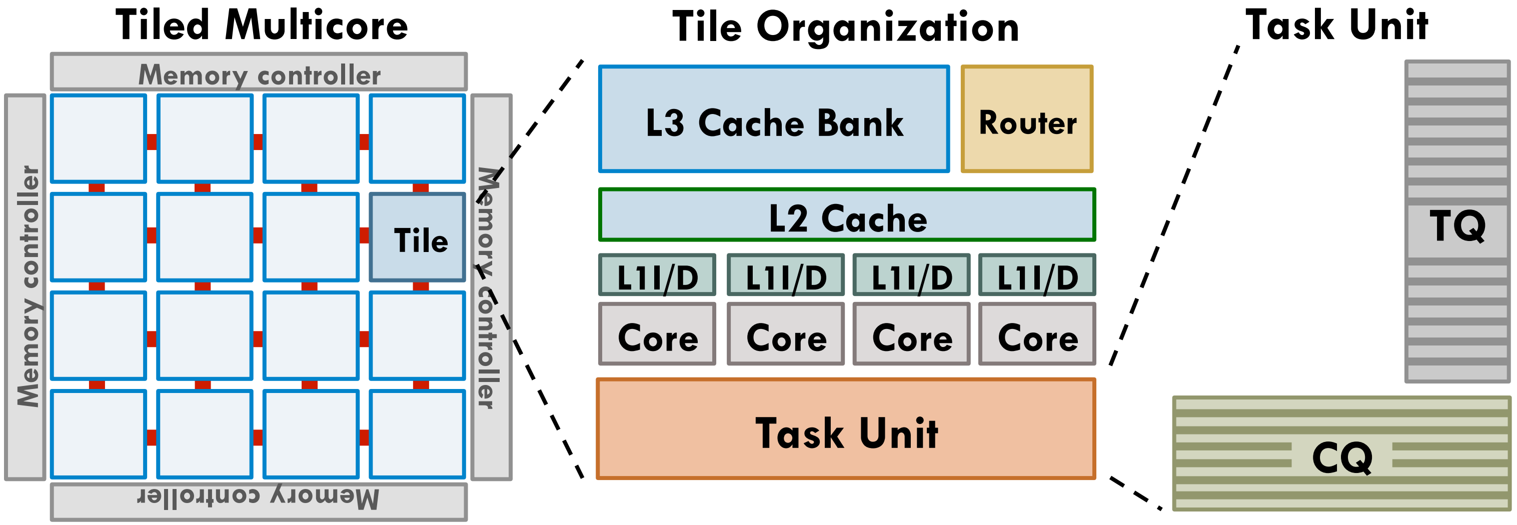

Per-tile task units:

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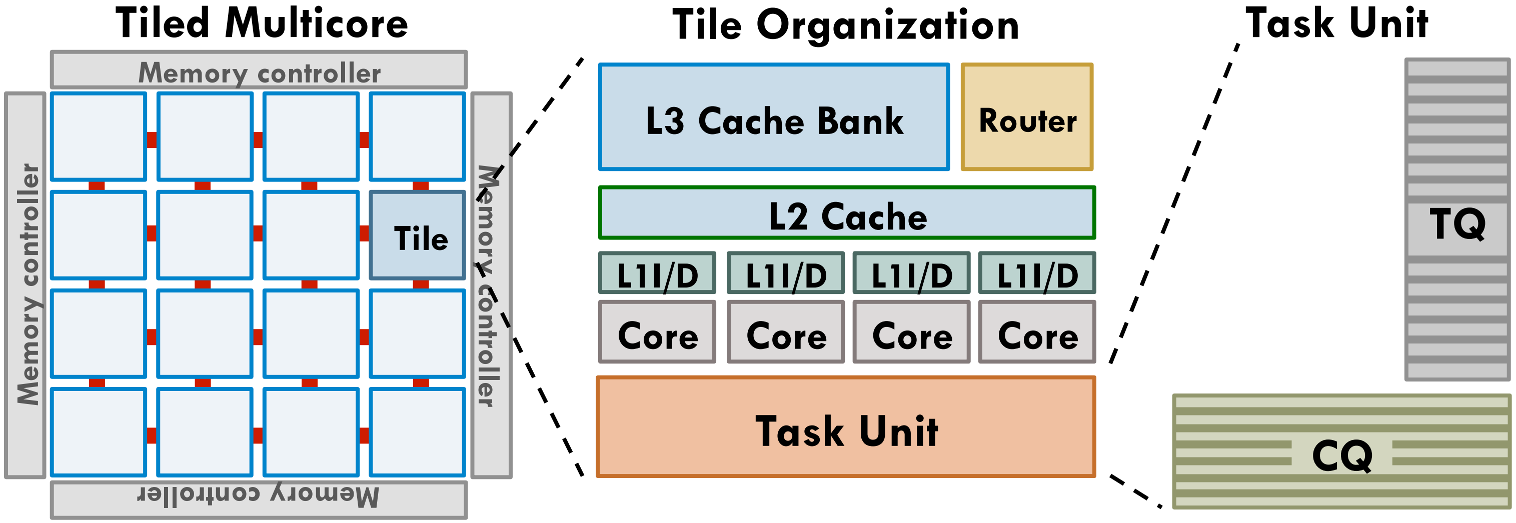

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Commit queues provide the window of speculation

# Task Unit Queues

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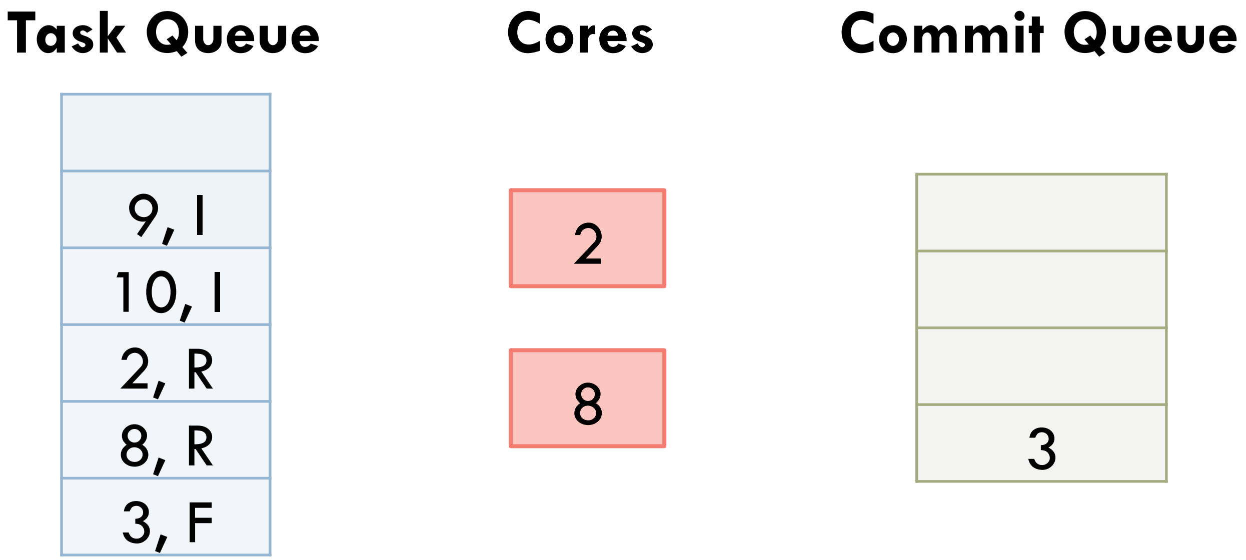
- **Commit Queue:** holds speculative state of finished tasks

**Task States: IDLE (I) RUNNING (R) FINISHED (F)**



**Task Queue**

9, I
10, I
2, R
8, R
3, F

**Cores**

2
8

**Commit Queue**

3

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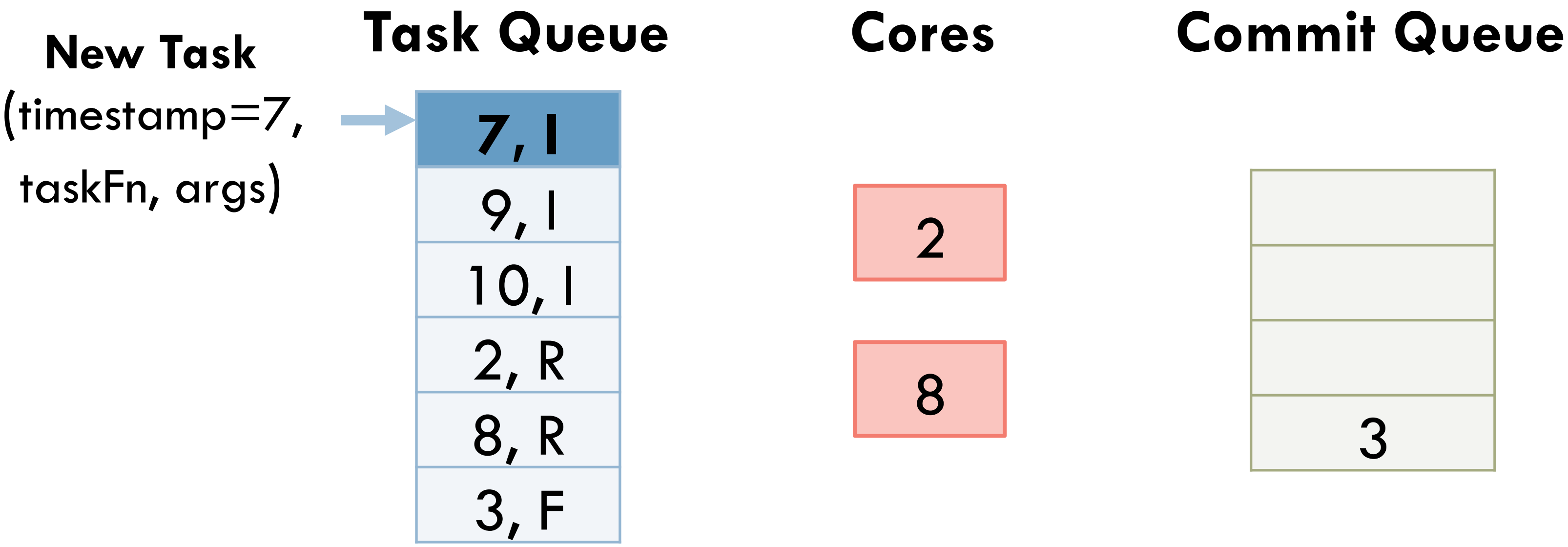

**New Task**
(timestamp=7, taskFn, args)

**Task Queue**

**7, I**
9, I
10, I
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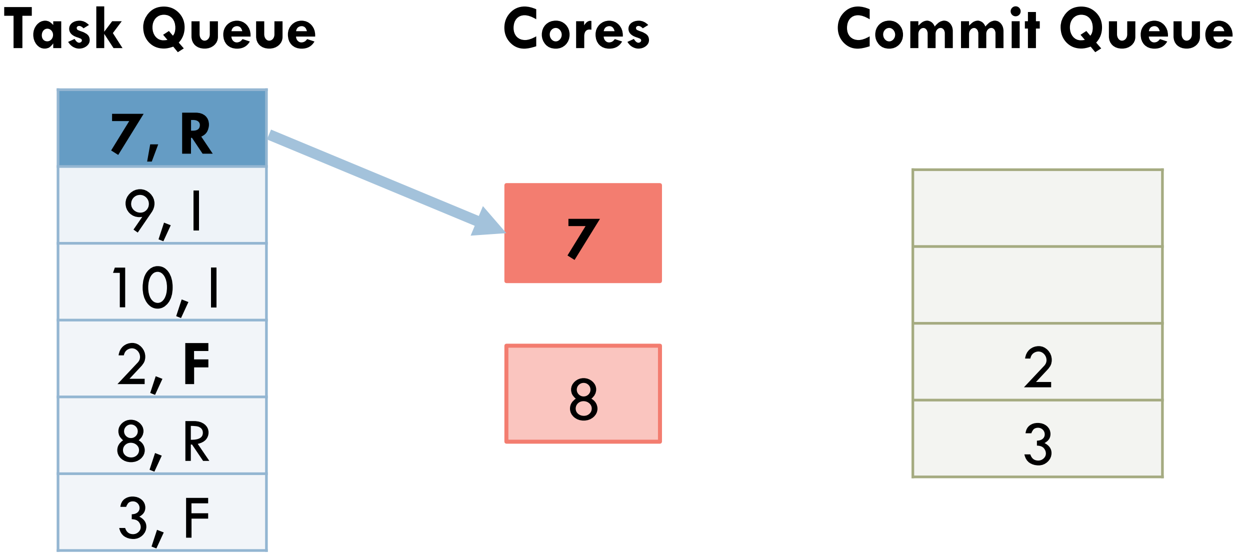

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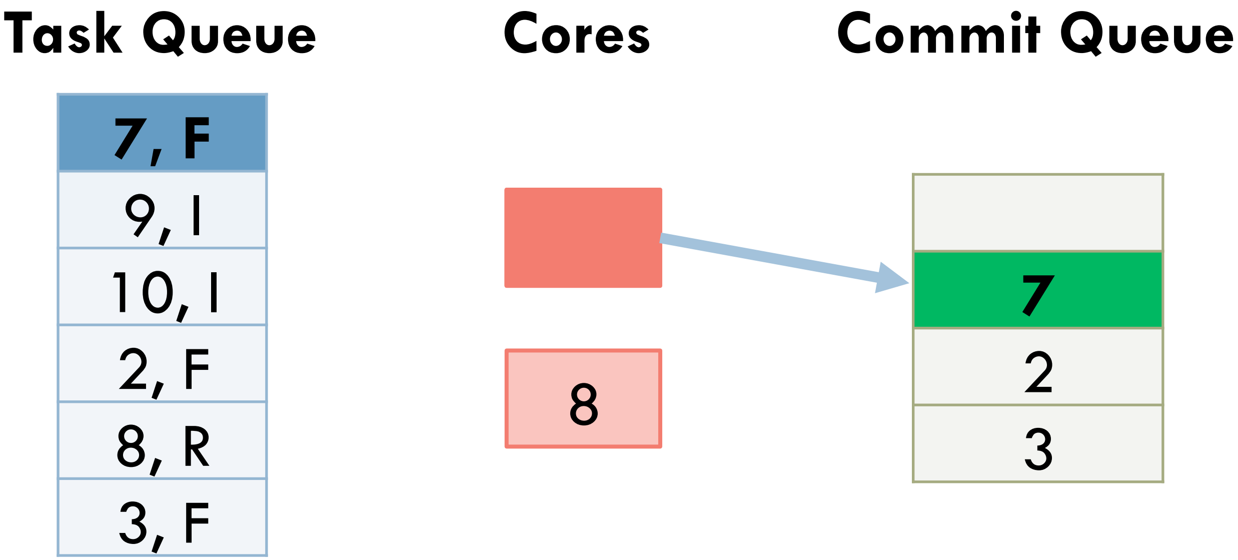

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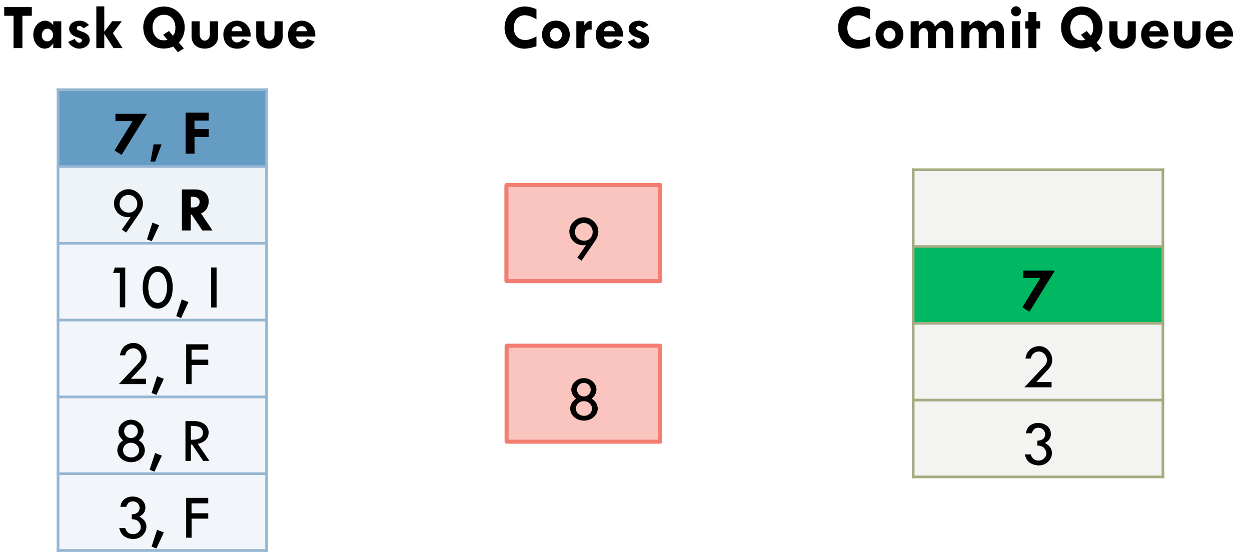

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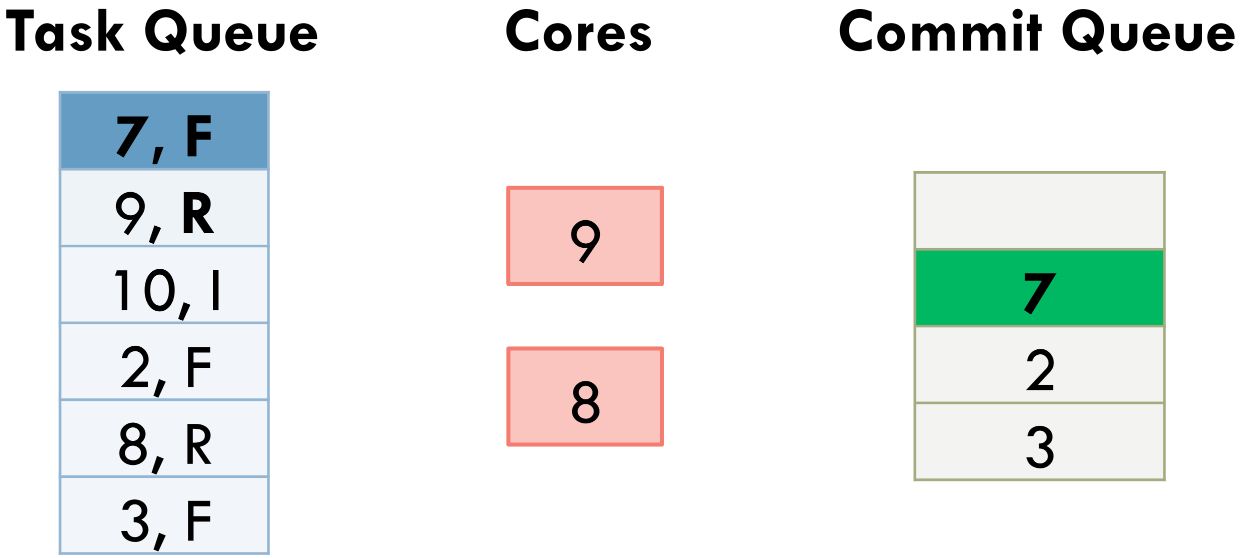

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**Cores**

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**Commit Queue**

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3

**Similar to a reorder buffer, but at the task level**

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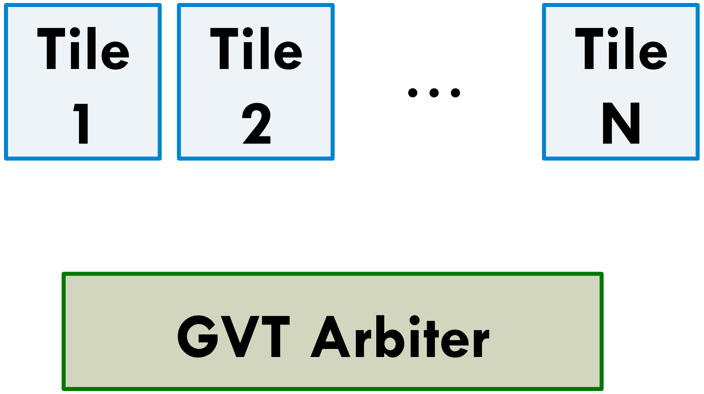

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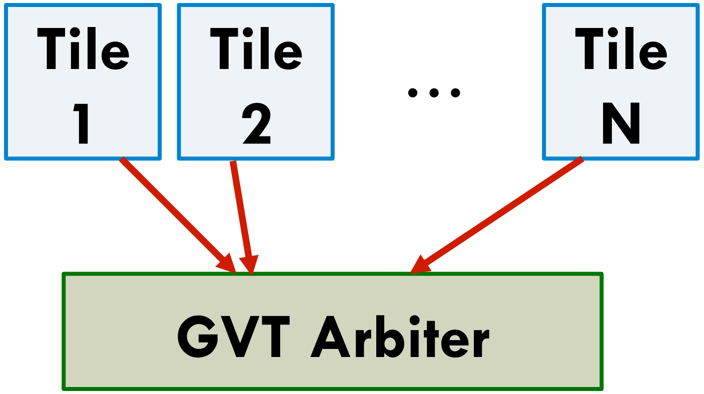

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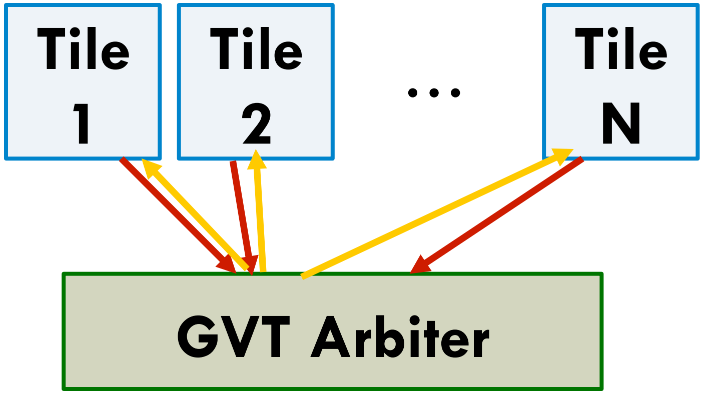

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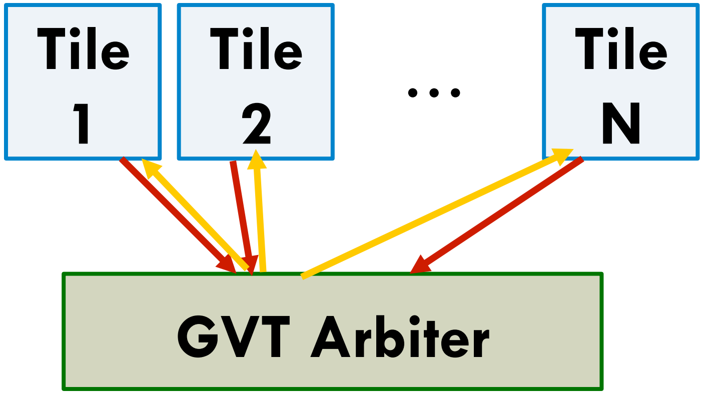

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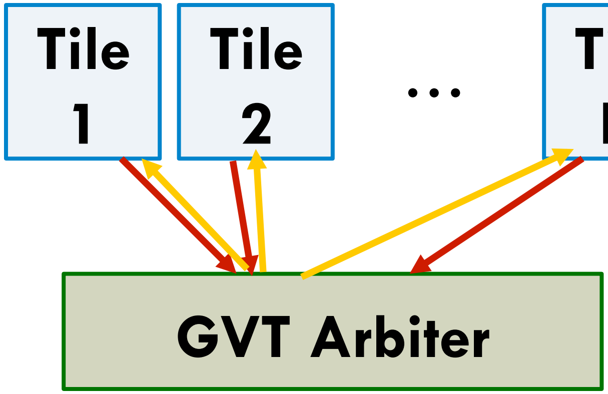

Tile 1

Tile 2

…

Tile N

GVT Arbiter

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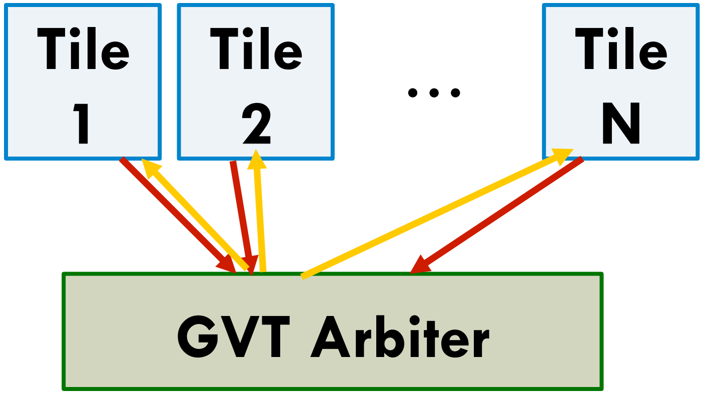

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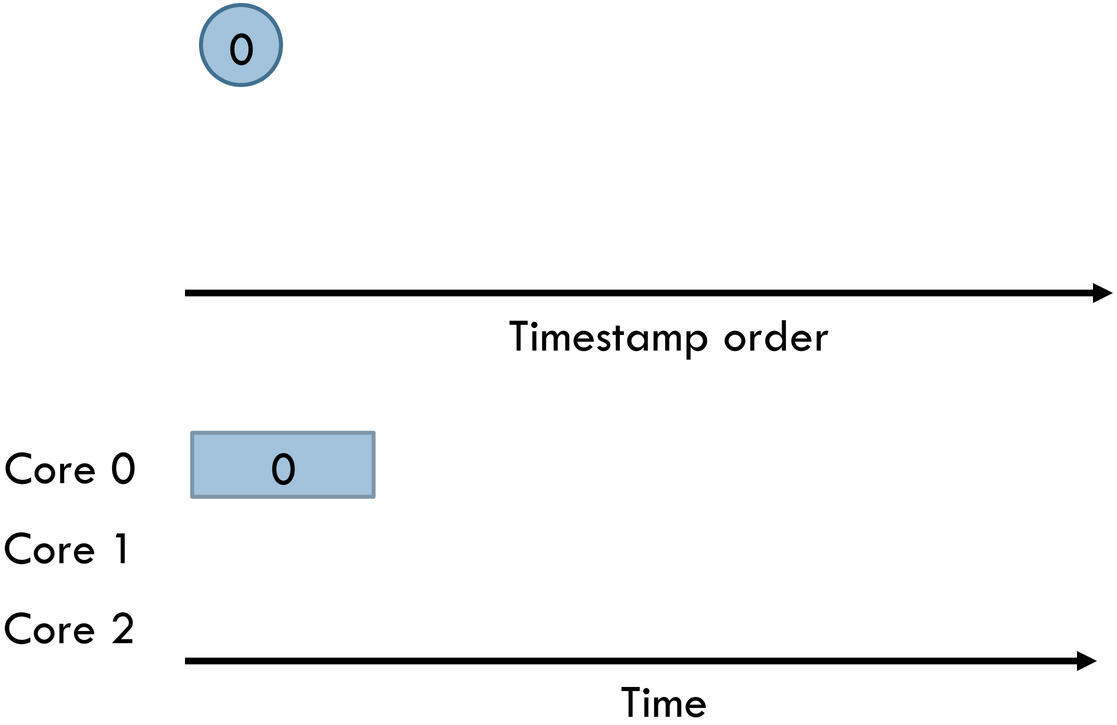
Amortizes commit costs among many tasks

# Speculative Execution Example



0

Timestamp order

Core 0

Core 1

Core 2

0

Time

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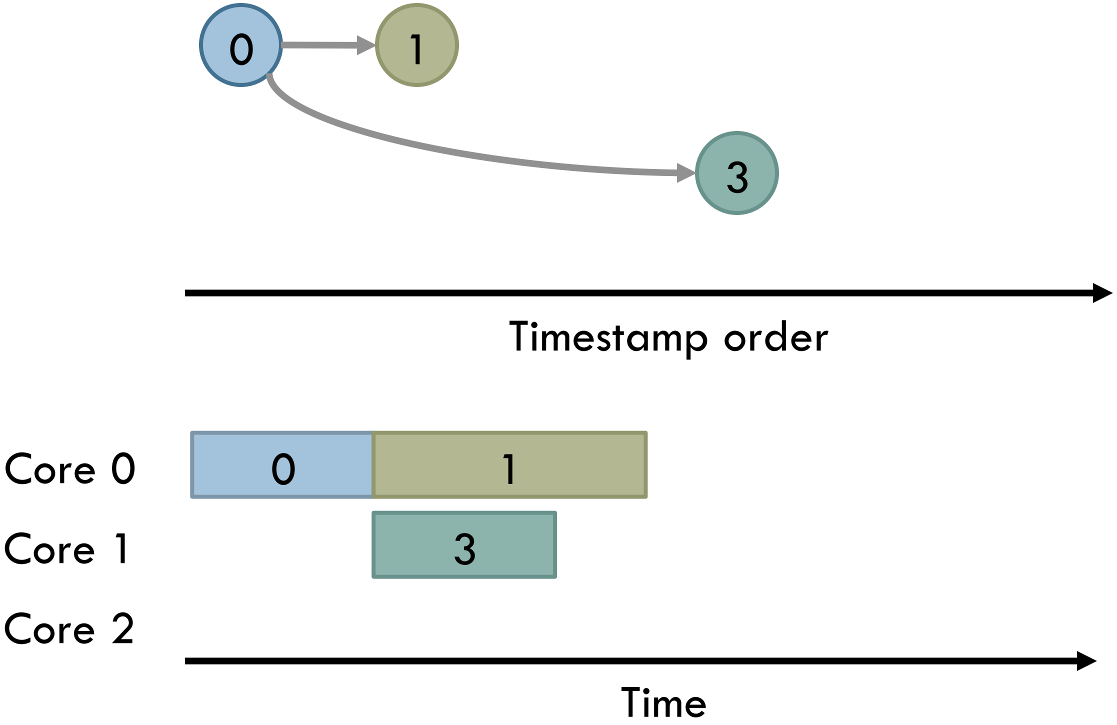

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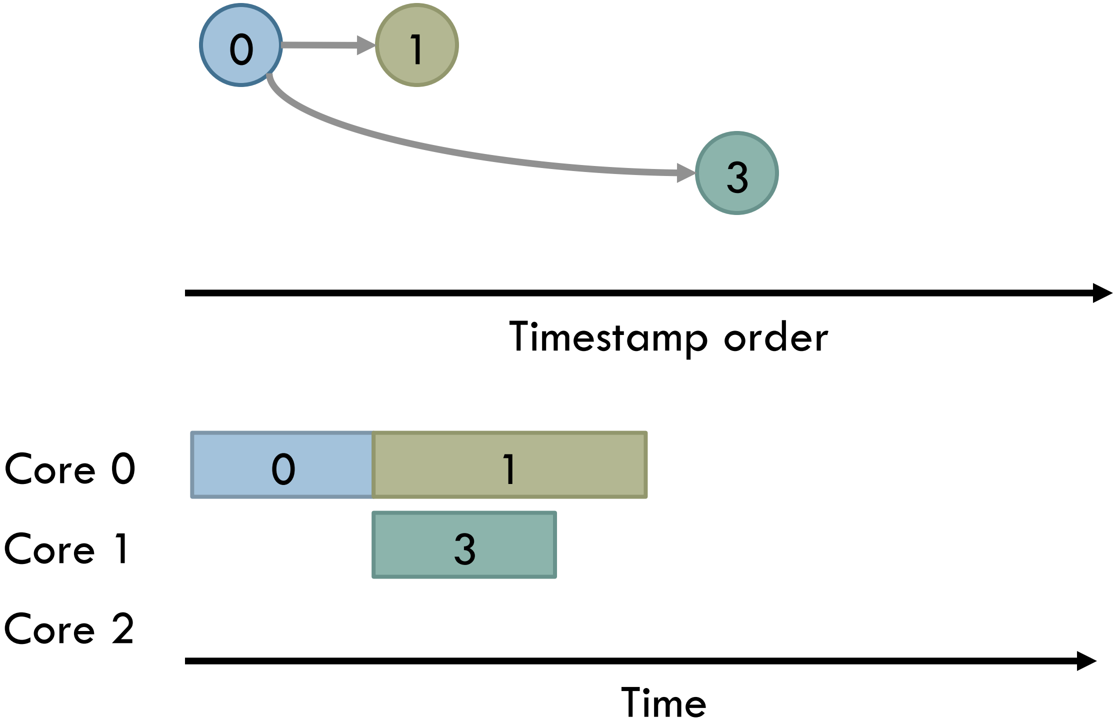

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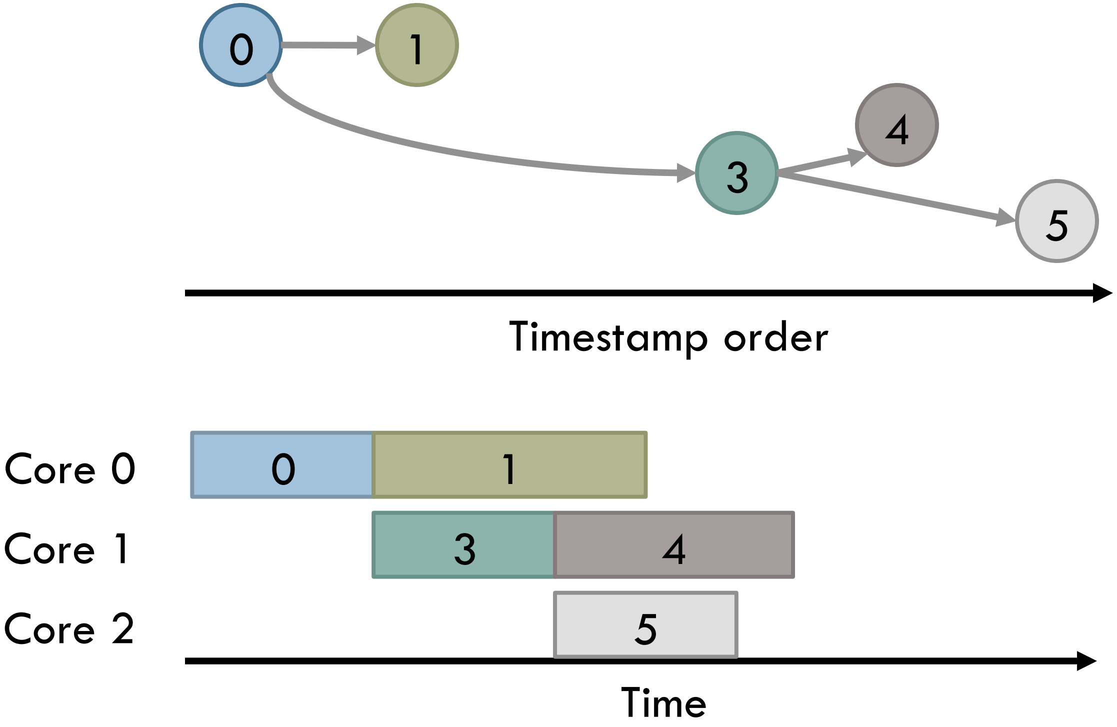

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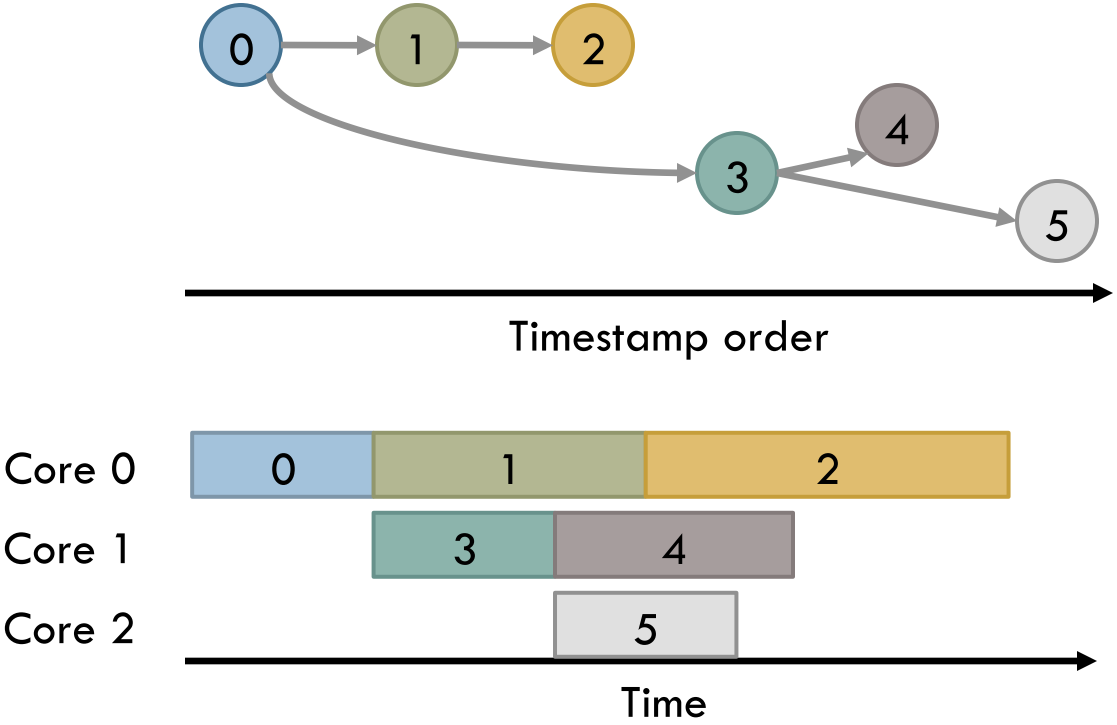

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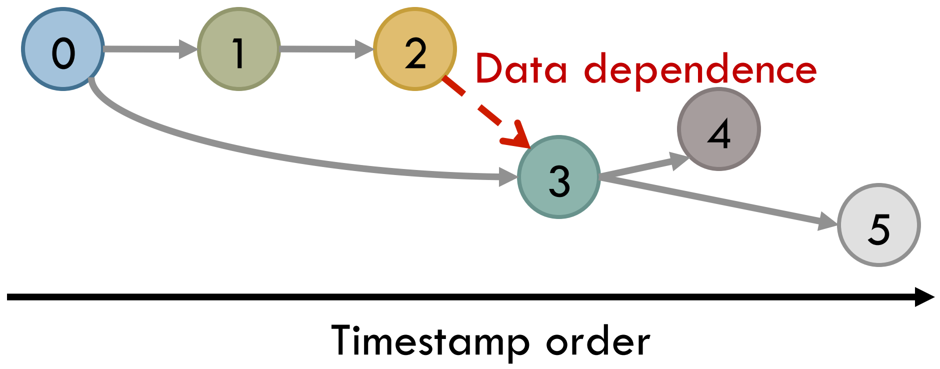

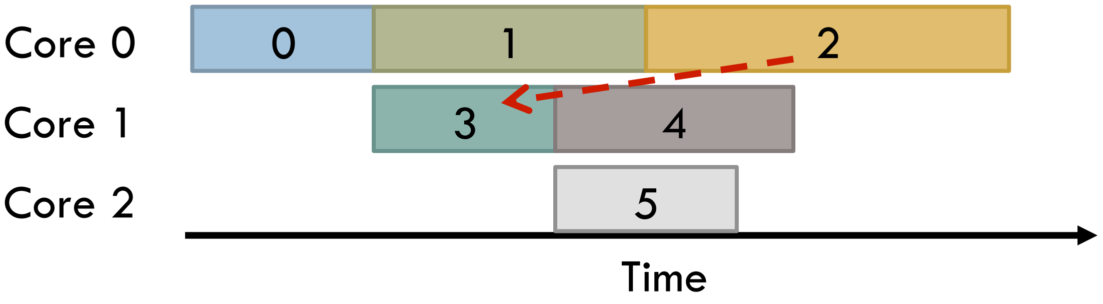

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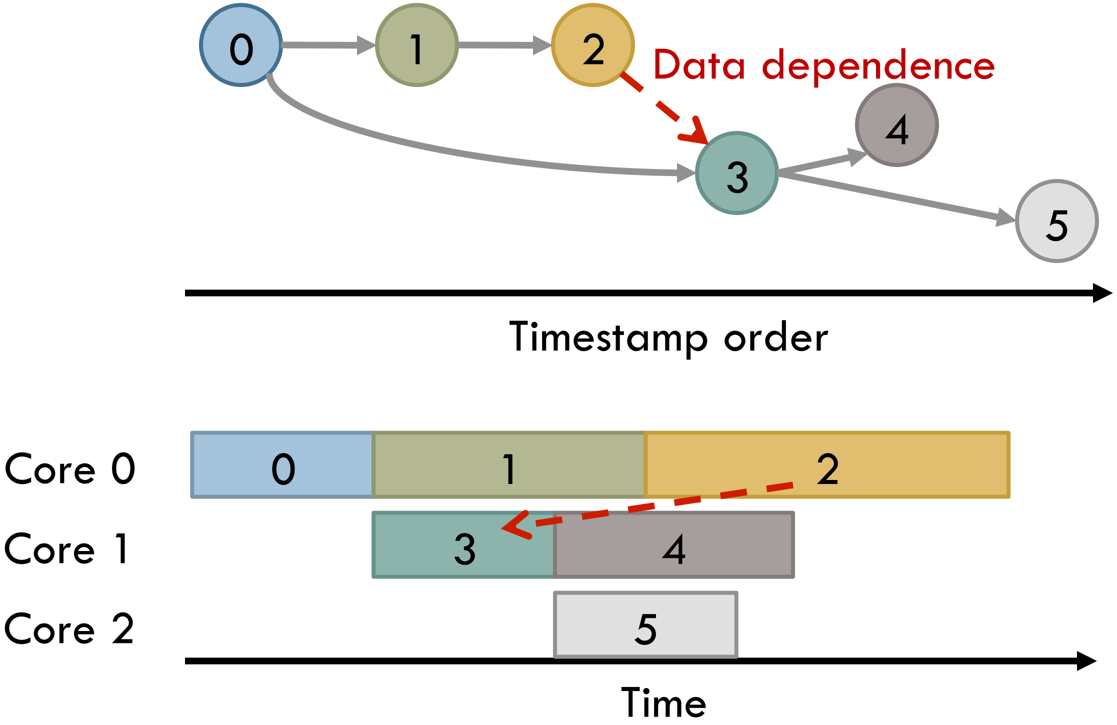

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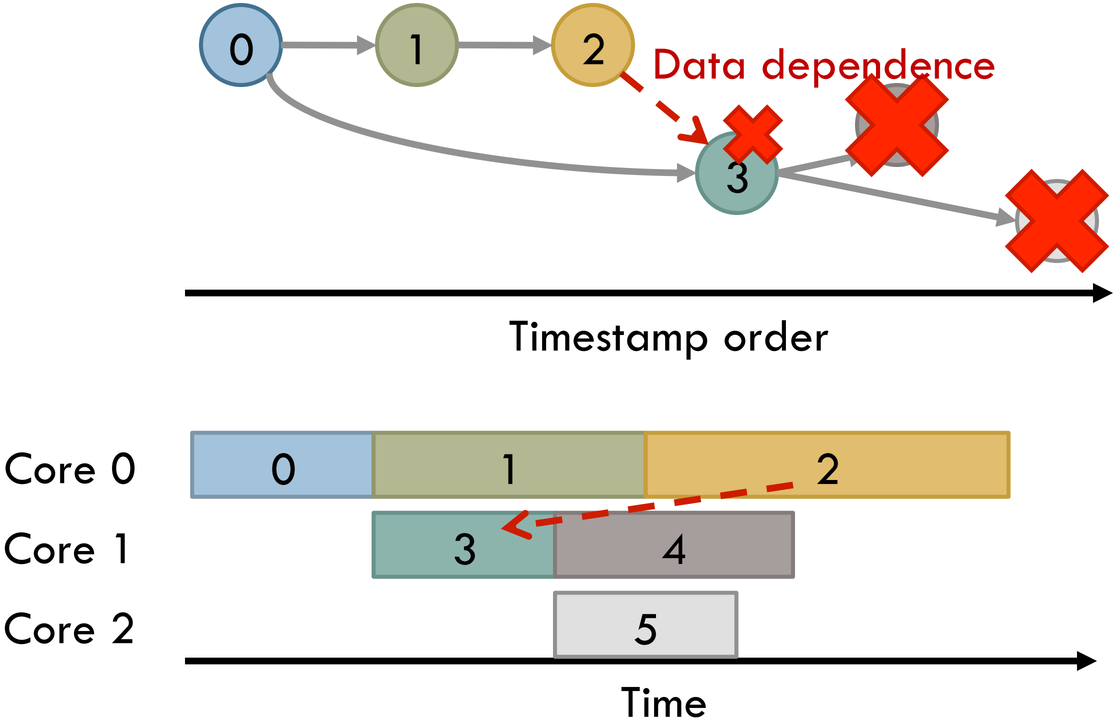

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- Enables two helpful properties
  1. **Forwarding** of still-speculative data
  2. On rollback, corrective writes **abort dependent tasks only**

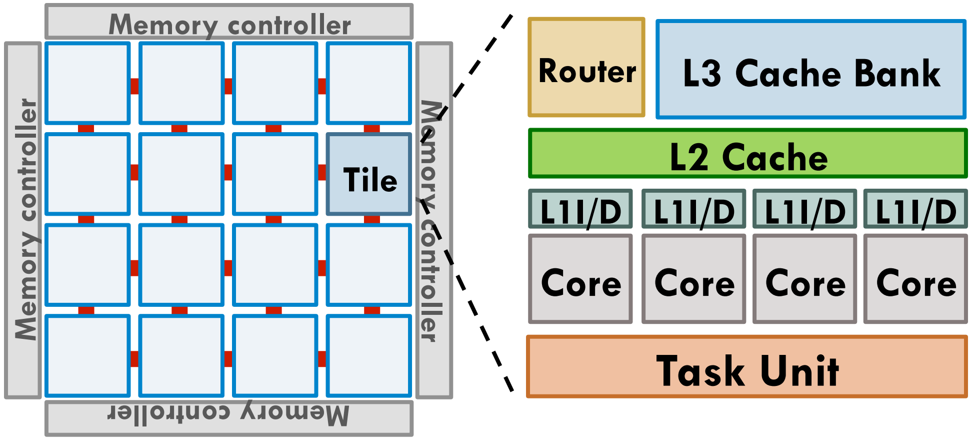
# Outline

- □ Understanding Ordered Parallelism
- □ Swarm
- □ Evaluation

# Evaluation Methodology

- □ Event-driven, sequential, Pin-based simulator

- □ Target system: 64-core, 16-tile chip



16 MB shared L3 (1MB/tile)

256 KB per-tile L2s

32 KB per-core L1s

4096 task queue entries (64/core)

1024 commit queue entries (16/core)

256-byte, 8-way Bloom filters

# Evaluation Methodology

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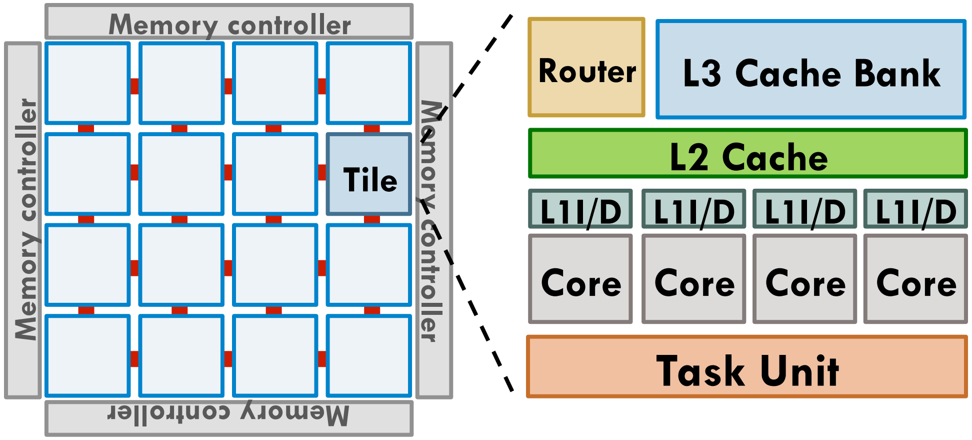

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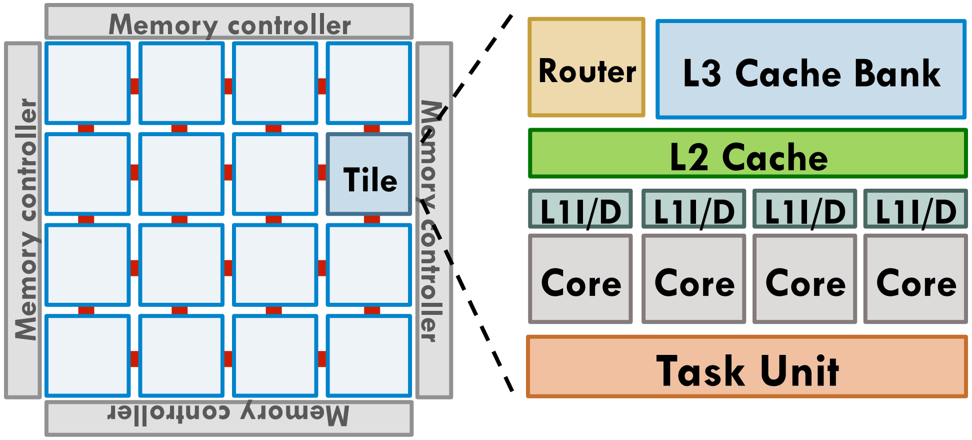

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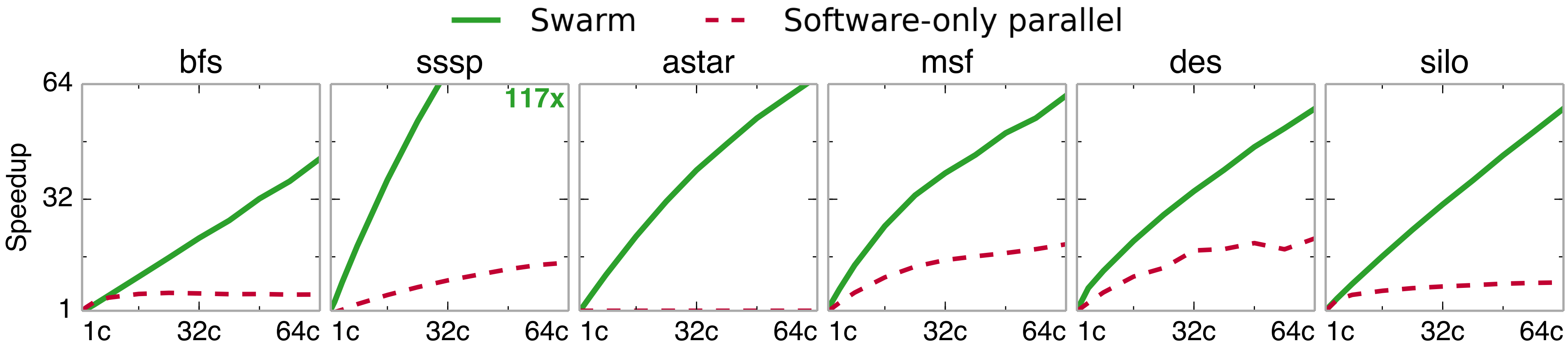
- Scalability experiments from 1-64 cores
  - Scaled-down systems have fewer tiles

# Swarm vs. Software Versions



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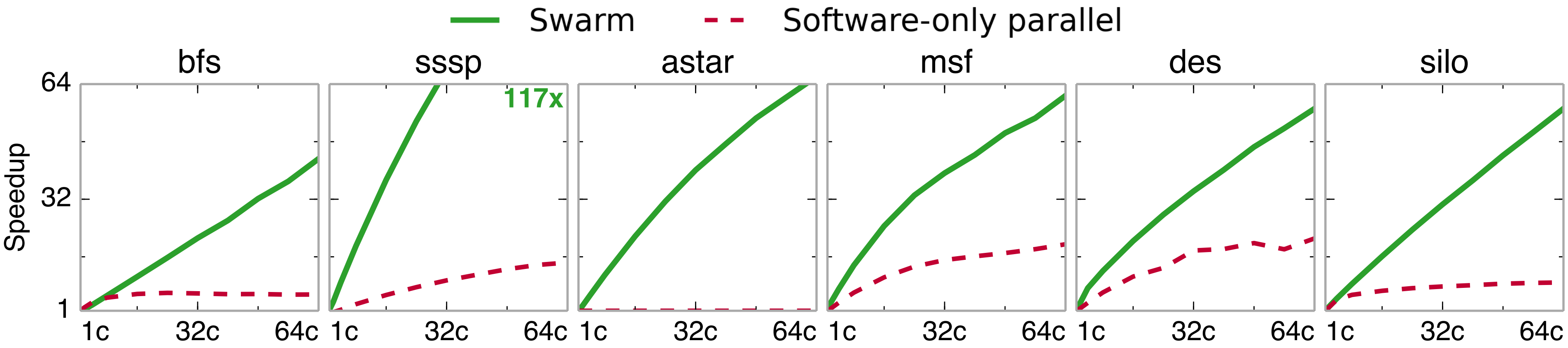

**43x – 117x faster than serial versions**

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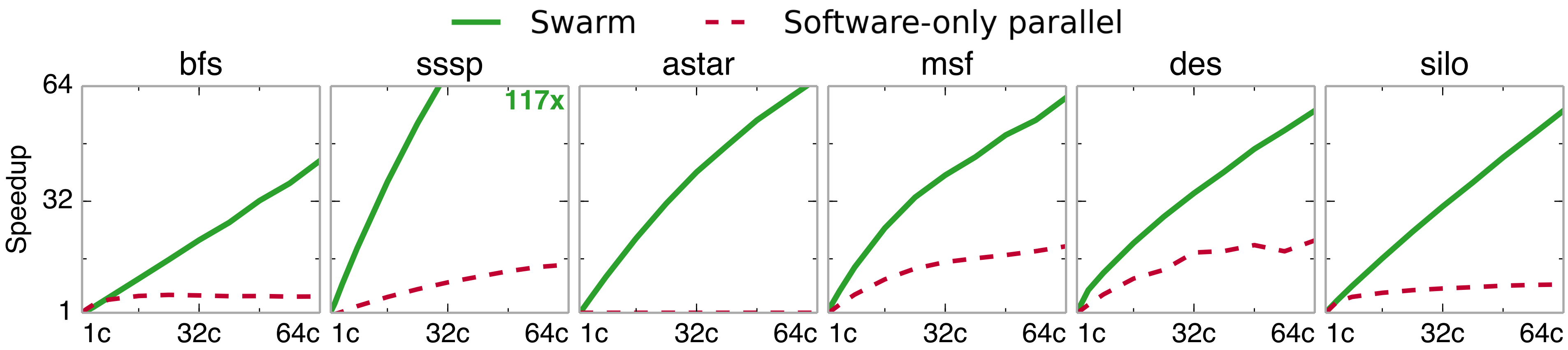

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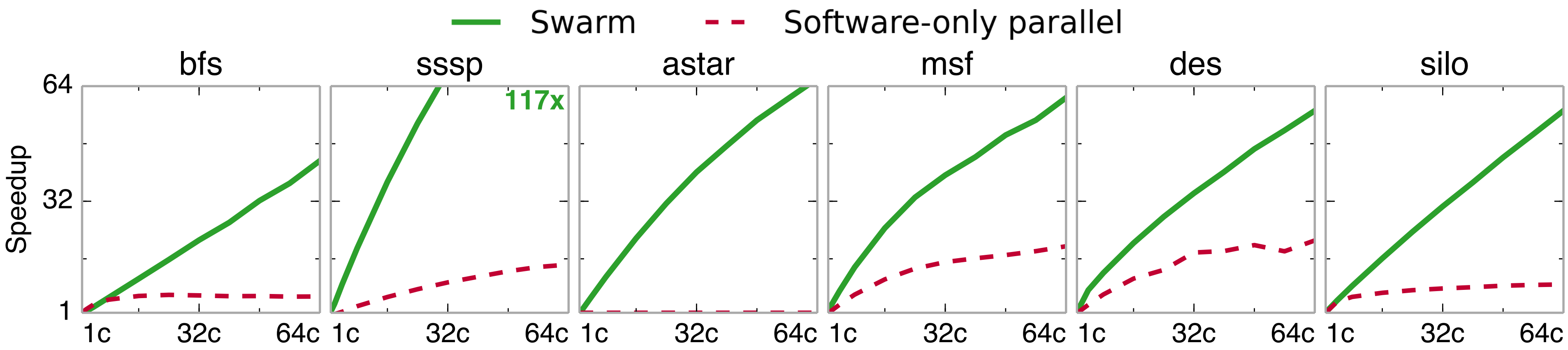

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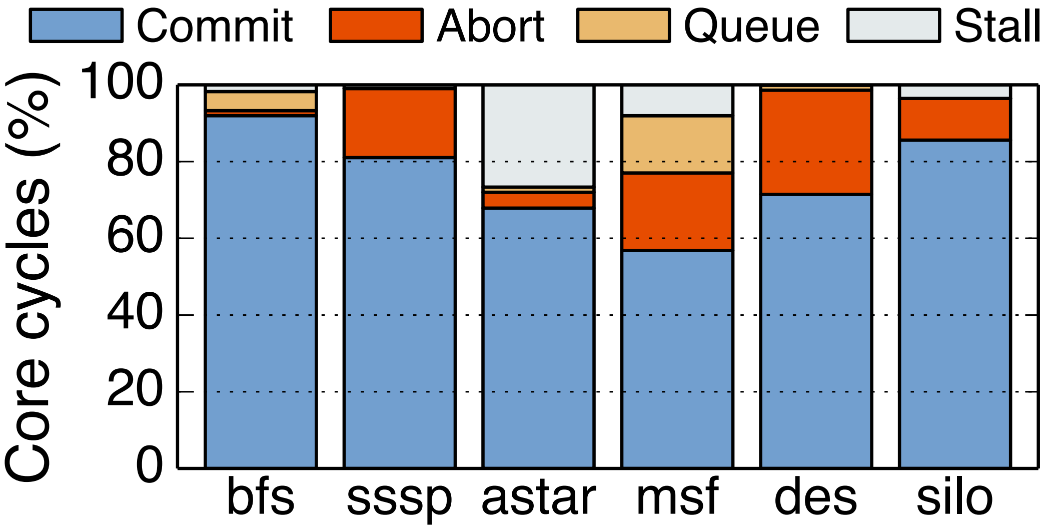
**Simple implicitly-parallel code**

# Swarm Uses Resources Efficiently



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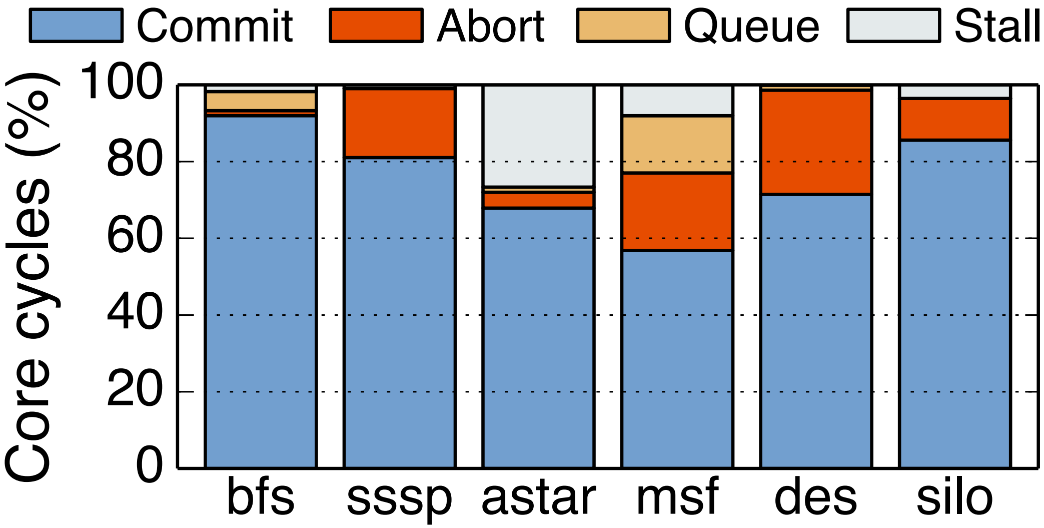

**Most time spent executing tasks that commit**

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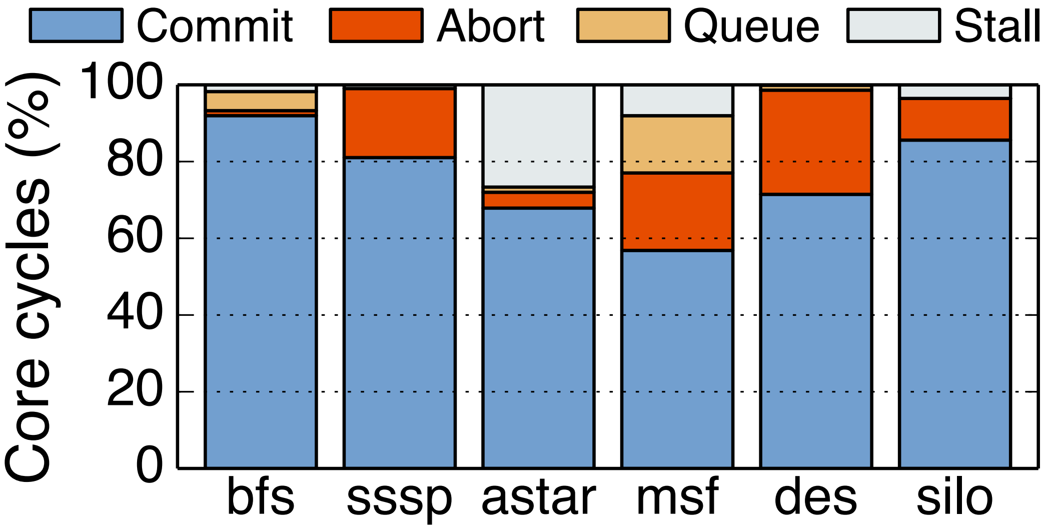

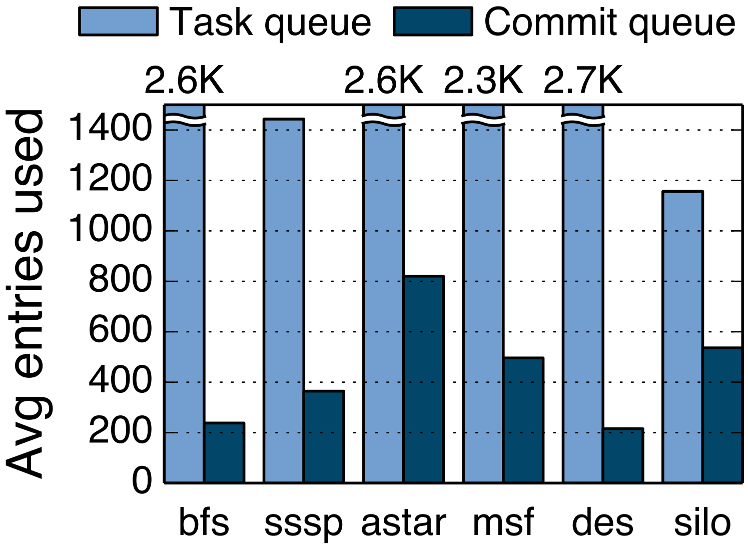

**Most time spent executing tasks that commit**

**Swarm speculates 200-800 tasks ahead on average**

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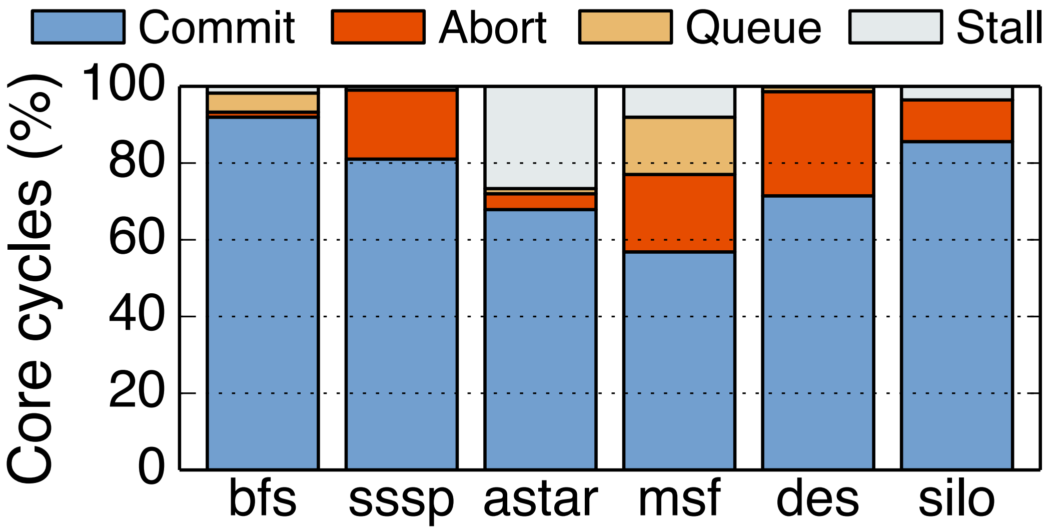
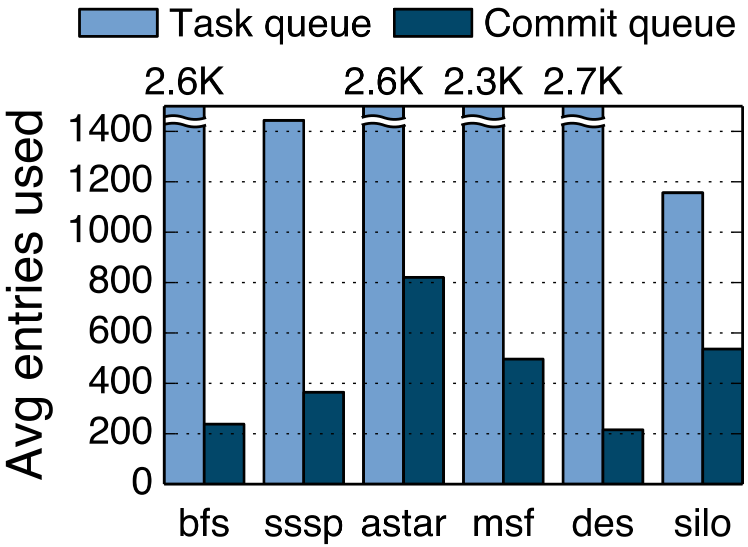




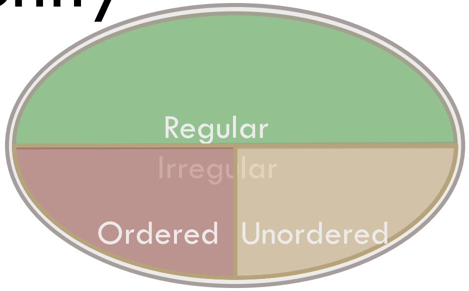
**Most time spent executing tasks that commit**

**Swarm speculates 200-800 tasks ahead on average**

- Speculation adds moderate energy overheads:
  - 15% extra network traffic
  - Conflict check logic triggered in 9-16% of cycles

# Conclusions

- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



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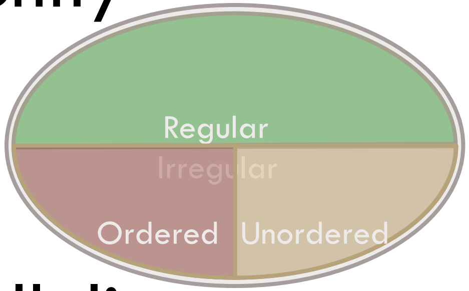

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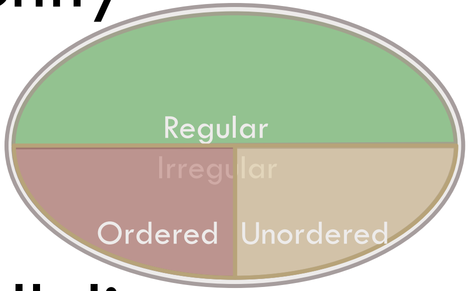

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Expressive execution model + large window =
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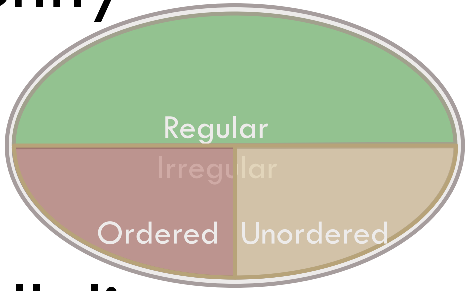

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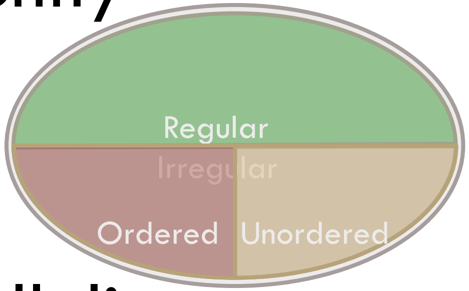

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- ~~Conventional wisdom: Speculation is wasteful~~

  Speculation unlocks plentiful ordered parallelism

  Can trade parallelism for efficiency (e.g., simpler cores)

# Thanks for your attention!
# Questions?

*A Scalable Architecture for Ordered Parallelism*

Mark Jeffrey, Suvinay Subramanian, Cong Yan,
Joel Emer, Daniel Sanchez

Massachusetts Institute of Technology

CSAIL

NVIDIA